NASA CONTRACTOR REPORT 177421

CONTROLLED ECOLOGICAL LIFE SUPPORT SYSTEMS (CELSS) CONCEPTUAL DESIGN OPTION STUDY

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CELSS

FOREWORD

The Conceptual Design Option Study- Controlled Ecological Life Support System (CELSS) Program Planning Support (Contract NAS2-11806) was initiated February 28, 1984 and completed December 31, 1985. This contract was an extension of the Regenerative Life Support/Controlled Environment Life Support System contract completed in 1983 for NASA Ames Research Center. The Contracting Officer's Representative was Dr. Robert MacElroy.

This study was conducted by the Boeing Aerospace Company, Seattle, WA.

The study final report is contained in two volumes as shown below:

D180-29490-1 Final Study Results
D180-29490-2 Final Study Appendix C ECLSS trade analysis

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GLOSSARY

CELSS	controlled environment life support system
CRES	corrosive-resistant steel
ECLSS	environmental control and life support system
ECS	environmental control system
HID	high-intensity discharge
IR	infrared
LEO	low Earth orbit
ORU	orbital replacement unit
PCM	parametric cost model
PGU	plant growth unit
ppm	parts per million
PRICE H	RCA parametric cost model for hardware
RLSR	Regenerative Life Support Research (program)
ROM	rough order of magnitude
SCWO	supercritical water oxidation
SE&I	system engineering and integration
STS	Space Transportation System (shuttle)
UV	ultraviolet

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1.0 INTRODUCTION

1.1 OVERVIEW

This document contains the results of the Controlled Environmental Life Support System (CELSS) study (NAS2-11806) originated by NASA Ames Research Center. The study approach, analysis procedures, results, and source data are presented in this document. Response to the CELSS Interim Conceptual Design Review document, published in August 1984, provided the commentary and discussion used in shaping the format and focus of this document. The document presents various options for the development of a CELSS design for a future space station. Research facilities that may lead to the CELSS module, such as the Life Sciences Research Facility and Ground-Based Plant Growth demonstrator, may benefit from the study results, as well as planning for longer range missions (e.g., lunar base and manned missions to Mars).

1.2 BACKGROUND

The CELSS program is a long-term research and development effort that addresses the future needs of NASA for recycling and regenerating materials needed for human sustenance during extended space missions. Long-term research and development programs always have inherent uncertainties associated with them. Uncertainties occur when mission specifics are not identified: specific outcomes of research tasks cannot be foreseen, inventions cannot be predicted, and specific test results cannot be scheduled. The solution to these uncertainty problems is to develop a flexible, planned approach of supporting research and development for long-term generic missions.

NASA has taken significant strides toward establishing long term goals and identifying potential mission areas requiring CELSS technology. Mission area identification was addressed in the Regenerative Life Support/Controlled Ecological Life Support Mission Model Study (NAS2-11148) conducted for NASA by Boeing Aerospace Company. Five generic missions were identified where the application of CELSS technology would be beneficial. In addition, critical data gaps were identified in the CELSS data base with respect to CELSS weight and cost estimates. These data base gaps were addressed during the current study by developing and analyzing a series of conceptual designs.

1.3 STUDY OBJECTIVES

The primary study objectives are to develop weight and cost estimates for a projected CELSS module based on preliminary designs. The estimates are to be compared with those used in the Regenerative Life Support Research/Controlled Ecological Life Support System Program Planning Support (Transportation Analysis) Study (NAS2-11148). This comparison will determine the validity of the conclusions reached in the transportation analysis.

Study objectives are met by—

a. Developing a minimum of six Space Station CELSS module conceptual designs. These designs are for review by NASA and other CELSS related personnel and are to be used as a springboard to selecting a preliminary baseline design candidate.

b. Conducting a CELSS module preliminary design effort to identify components and subsystem relations.

c. Conducting a sensitivity analysis of the CELSS subsystems.

d. Developing a research topical listing to aid in directing future research and development efforts.

1.4 STUDY APPROACH

A four-step study approach was used to attain weight and cost estimates. First, multiple conceptual design options were developed for review by NASA and personnel associated with the CELSS program. Second, a CELSS module preliminary design was produced based on the first step and comments received from NASA during the conceptual design stage. Third, weight and cost estimates were developed using preliminary design data for equipment lists and sizings. Fourth, a parametric sensitivity analysis was conducted using the preliminary design cost and weight data.

The documentation was developed parallel the study effort. This documentation approach allows the reader to follow the design flow and decision processes that went

into preliminary design development. A research area topical identification listing was formed that identified research areas where insufficient information was available to support CELSS module design. The topical listings are divided into three research area categories that are key to CELSS design development: biological research, engineering research, and technology development.

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2.0 STUDY SUMMARY

Study results support the premise that an operational CELSS research module will not create unacceptable demands on Space Station support services. A general CELSS requirement summary (Table 2.0-1) indicates that -

a. The CELSS system would require approximately 56.9 m^3 of space per man for plant growth area, support equipment, and access.

b. The degree of CELSS system automation can be very high; one man can tend the growing area for a large crew (8 to 12 crewmen) with time for other duties. The daily average for man tending should be less that 0.5 hr for routine tasks.

c. Based on preliminary design, approximately 21 000 kg will need to be lifted into orbit for a two-man module. This includes module and equipment but not initial consumables.

d. Based on preliminary design, resupply should not exceed 764 kg per 90 days, but is highly dependent on CELSS system design.

e. Electrical power requirement can range from an average of 6.8 kW for a fiber optic solar collector system to 87.7 kW for a 24-hr/day artificial lighting system. Electrical power requirement for maintaining continual illumination (using a combination of 16-hr solar and 8-hr artificial lighting) are 8 kW light side and 17 kW dark side. This provides full intensity (750 μmole/m^2/s) light-side illumination using solar collectors and one-tenth intensity (75 μmole/m^2/sec) dark-side illumination using artificial lights.

Volume requirement	56.9 m^3 per man
Crew time	0.5 hr per day
Lift to orbit including module	21 000 kg
Resupply per 90 days	763.9 kg
Electrical power (all fiber optic system)	6.8-kW average
Electrical power (all artificial light system)	87.7-kW average
Illumination level (full)	750 μmol/m^2/h
Illumination level (power conservation mode)	75 μmol/m^2/h

Table 2.0-1. CELSS General Parameters Summary

Comparing Space Station module costs (fig. 2.0-1) shows that the CELSS module costs ($590 million) are slightly lower than those for a comparable laboratory module (e.g.,

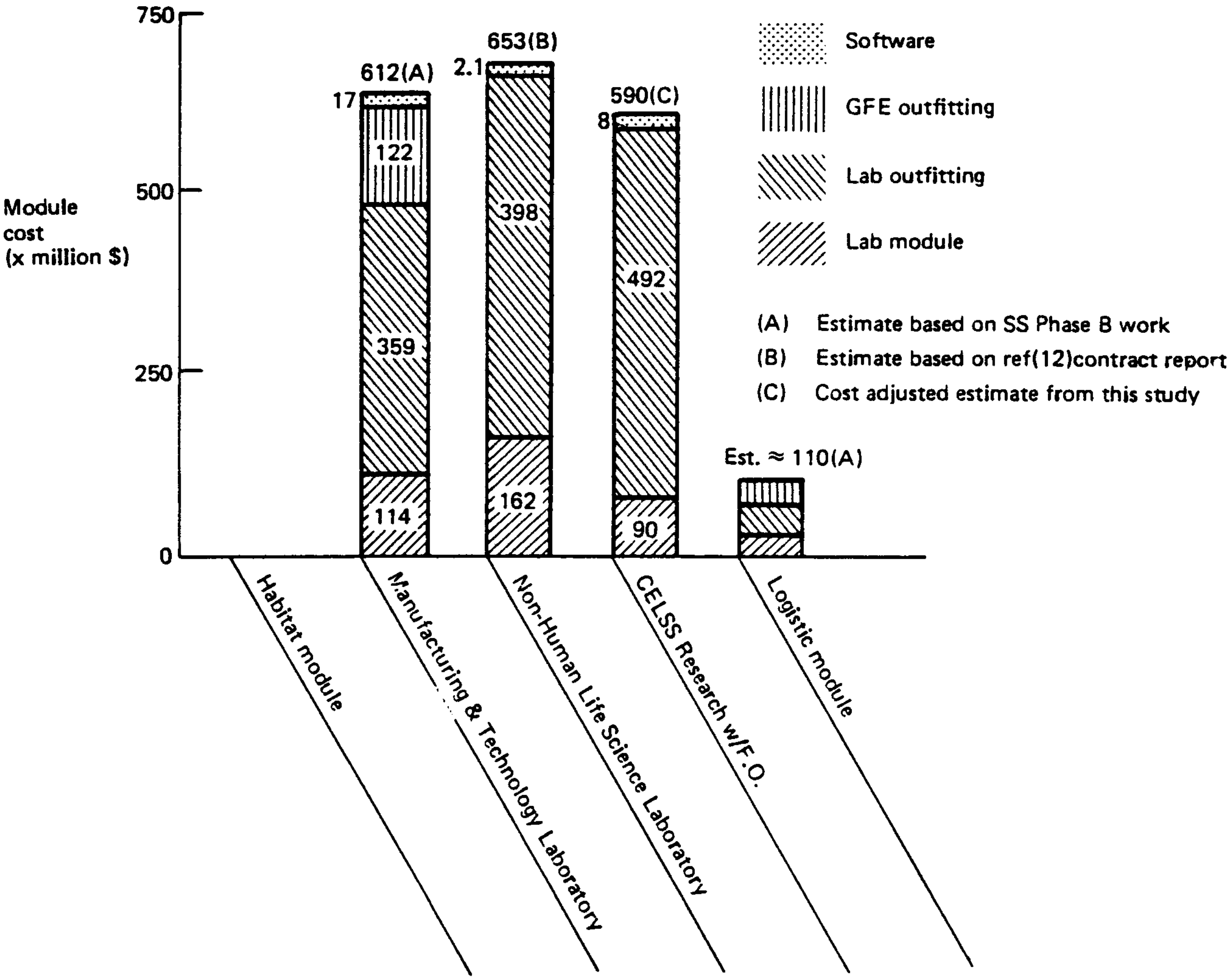

Figure 2.0-1. Space Station Module Cost Comparison

Life Science Research module, \$653 million, or Manufacturing and Technology Laboratory module, \$612 million). Further analysis demonstrates that cost per man can be reduced as the module size is increased (fig. 2.0-2) because overhead costs remain relatively constant for support equipment when additional plant growth units (PGU) are

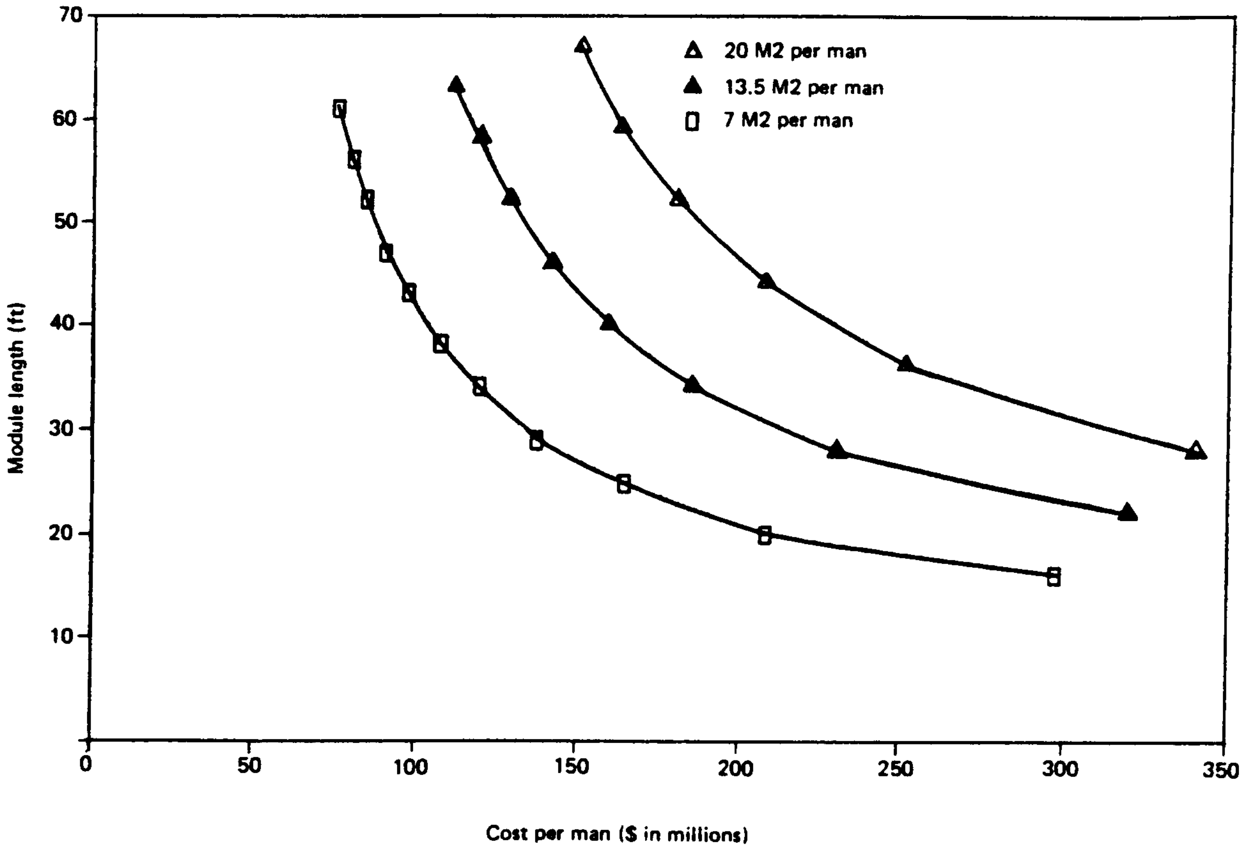

Figure 2.0-2. Cost Per Man by CELSS Module Length

added. Additional improvement in CELSS cost effectiveness occurs when plant growth area required to support one man is decreased (fig. 2.0-3). The improvement is in both cost per man and an increased number of men supported per module.

This study validates the power, mass, volume, and cost conclusions developed in the Regenerative Life Support Research Controlled Ecological Life Support Study (RLSR/CELSS), conducted in 1982, by showing the systems weights used are reasonable and correct. The break-even calculations in the RLSR/CELSS study are found to be based on realistic masses, power, and cost values. The RLSR/CELSS study demonstrated a potential break-even point of 7.5 years for low Earth orbit (LEO) CELSS system based on a mass of 6750 kg/person. Data from the current study estimate a mass of 6472 kg/person; a 4.1% difference. This suggests that inclusion of a CELSS module, even in the currently proposed Space Station, could be beneficial economically and

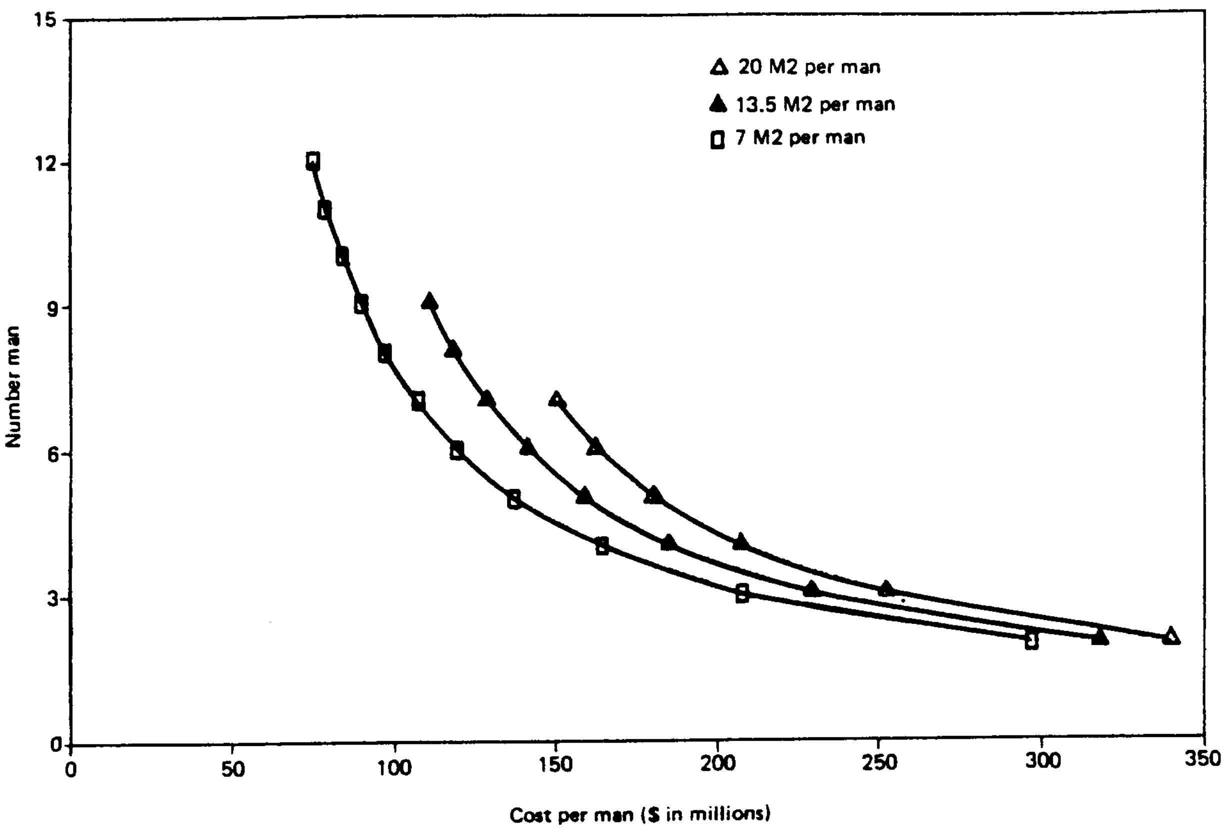

Figure 2.0-3. Cost Per Man Versus Number of Men Supported by One CELSS Module

scientifically. Volume comparisons are within 10%, 56.9 m^3 current study versus 51.15 m^3 RLSS/CELSS. Electrical power value difference stems from different approaches to lighting systems. The RLSS/CELSS study uses a continuous, artificial illumination system emitting 500 $\mu mol/m^2/s$. This study uses combined fiber optic solar collectors and low-level artificial illumination to provide 750 $\mu mol/m^2/s$ during light-side orbit and 75 $\mu mol/m^2/s$ during dark-side orbit.

The design phase produced 11 concepts for evaluation and testing. A PGU structure was developed that held plant trays in place and allowed for positioning plant growth support equipment (e.g., nutrient supplies and lights). The selected PGU uses an accordion growth tube to economize on volume. The nutrient supply system features quick-disconnect fittings. Plant harvesting and processing designs are totally automatic for normal operations. Robotic gardening concepts are explored that use current robot capability combined with rudimentary artificial intelligence. This combination significantly reduces the human workload. Supercritical water oxidation (SCWO) provides a system with excellent potential for recovering nutrient salts. Using recovered salts can reduce the need for nutrient resupply from Earth by 40% to 90% depending on waste system configuration.

A sensitivity analysis, using the developed weight and cost data highlighted the parameters that most heavily impact CELSS design. This sensitivity analysis included mass, cost, electrical power, and volume evaluations. Systems that have the greatest affect on parameter values are identified in table 2.0-2.

Parameter	Mass	Cost	Volume	Power
1ST	Module	Lighting	PGU	Lighting
2ND	Lighting	Module	Module	Thermal
3RD	Thermal	Robotics	Lighting	Nutrient supply

Table 2.0-2. CELSS Systems Ordered by Impact on Parameter Values

Research area listings are provided to aid in determining future CELSS research topics (secs. 2.6 and 6). These listings reflect the areas where insufficient data was available for preliminary design. Listings are broken into biological research areas, engineering research areas, and advanced technology research areas.

Major study topics are summarized in the following subsections. Succeeding chapters provide detailed discussion of each topic.

2.1 DESIGN OPTION DEVELOPMENT AND REVIEW

Seventeen alternative conceptual designs were considered in this study. Three of these designs were selected for further review and refinement.

a. Accordion tray concept (fig. 2.1-1).
b. Automated warehouse concept (fig. 2.1-2).
c. Expandable tray concept (fig. 2.1-3).

These design options were selected based on consideration of -

a. Minimizing CELSS module mass. Reduced mass decreases launch costs and impact on Space Station attitude control.

b. Minimizing cost for each kilogram of edible biomass produced per day.

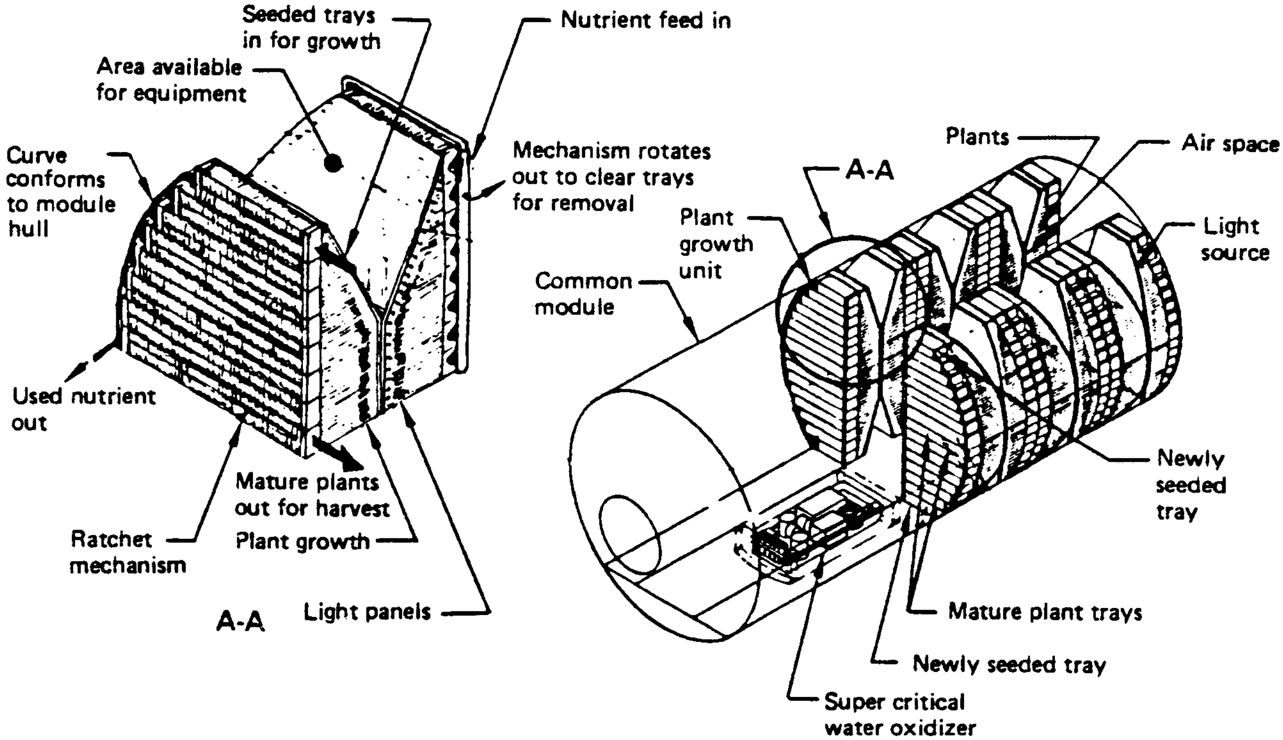

Figure 2.1-1. Accordian Tray Concept

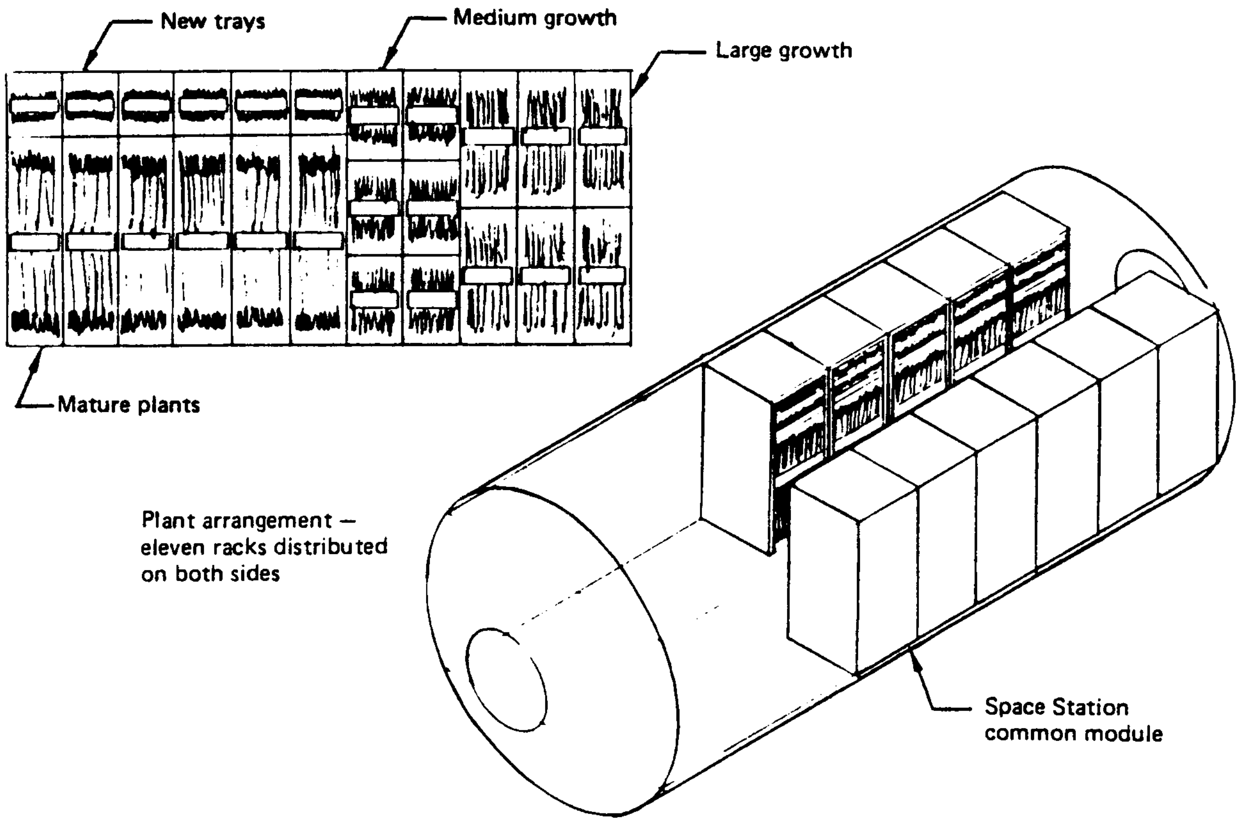

Figure 2.1-2. Automated Warehouse Concept

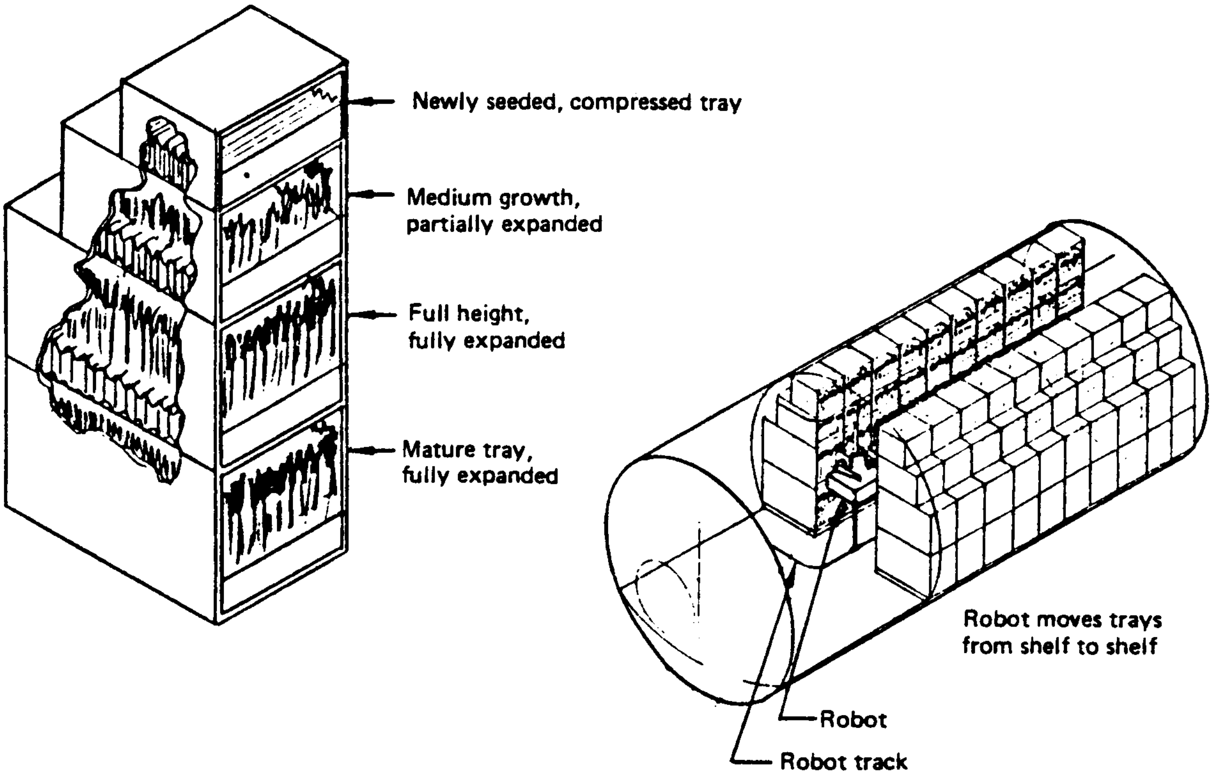

Figure 2.1-3. Expandable Tray Stack

c. Minimizing volume for each kilogram of edible biomass produced per day. Study guidelines dictate maximum volume available of 145 m^3 from which to feed two or more crew members. This requires compact PGUs with high packing densities within the module.

d. Minimizing power consumed for each kilogram of edible biomass produced per day. Electrical power is supplied by Space Station on an allocation basis. CELSS design must minimize power consumption to operate with allotted power while producing maximum food.

e. Mechanical reliability must be high to prevent plant loss due to equipment failure. High reliability also conserves crew time by reducing maintenance and repair activities.

f. Automated operation is necessary to reduce crew involvement. Crew time is a limited resource that must be conserved. The appropriate application for automation and robotic systems, while expensive, can recover cost in crew-time savings.

2.1.1 Conceptual Design Option Evaluation

Design options cover a wide range of possibilities. Final selected design for CELSS may vary slightly or significantly from those identified in this study. Each design considered during the study conceptual design phase is discussed below. All options are workable and can be built with existing technology. Designs selected are the compromised versions that produced the best yield at a minimal penalty to Space Station resources.

2.1.1.1 Accordion Concept

Accordion tray stack (fig. 2.1-1) met design criteria best and was selected for further development. Tray structure is more complex in accordion tray stack than in the other two concepts. This design used volume 77% better than the other two concepts because accordion trays permit small seeded areas to expand with plant growth; this also eliminates transplanting. This design is capable of growing different crops without major changes in the plant growth system.

2.1.1.2 Automated Warehouse Concept

Warehouse tray stack (fig. 2.1-2) is a conventional vertical stack of growth trays. Height of each compartment is tailored to the growth phase of the plants. Seedling spacing is the same as for mature plants due to nonexpanding trays and study guidelines prohibiting transplantation. This results in an inefficient use of volume in early growth stages. Warehouse tray stack is relatively simple to build and service.

2.1.1.3 Expandable Tray Concept

Expandable tray stack (fig. 2.1-3) combines vertical stacking of warehouse tray stack with accordion tray concept. This improves volume usage as trays are compressed during early stages of growth. Because trays must be placed in a limited number of tray openings sized for different stages of growth, the expandable tray stack does not optimize lighting as plants spend a period of time in compartments that are too tall for the plants. This places light source outside optimum range from the plant canopy. Expandable tray stack is mechanically simpler than accordion tray stack, but more complex than warehouse tray stack. Other design options are not pursued for reasons

outlined in section 3.0. These designs may be feasible under conditions not currently being considered for this contract.

2.2 PLANT GROWTH SUPPORT SYSTEMS

2.2.1 Plant Growth Unit

CELSS plant growth area uses a portion of a module similar to the common module but the floor and ceiling are farther apart.

There are 24 PGUs in the plant growth area. Each unit occupies a volume approximately 30 in wide by 66 inches high by 56 in deep. The floor-to-ceiling distance is occupied by two PGUs. Each side of the module has 12 PGUs (fig. 2.1-1).

Each PGU has eight trays, each tray is 8 in square by 56 in long when the collapsible tray bellows are extended. Tray structure is compressed along its length after a seed-carrying tape is applied over matched slots in the tray. The collapsed tray is inserted into the PGU in the position closest to the floor or ceiling (fig. 2.2-1), as the position 1. As plants in lower trays (position 8) mature, they are removed from the PGU. The bottom of all PGUs is in the vicinity of the module center (i.e., plant tray movement is from floor and ceiling toward the center of the module).

When mature plants are removed from the PGU, volume is available for the next tray to move down. This leaves space in the beginning of the PGU cycle for a newly seeded, collapsed tray to be inserted.

Table 2.2-1 summarizes PGU parameters. Electrical power data are expressed as the peak power demand for each system. Duty cycles express the percentage of time the system will be operating. (See sec. 6.4 for detailed electrical power demand and duty cycle discussion.) When more than one major system is called out under a single heading, as in this case each major system is called out with it's related parameters.

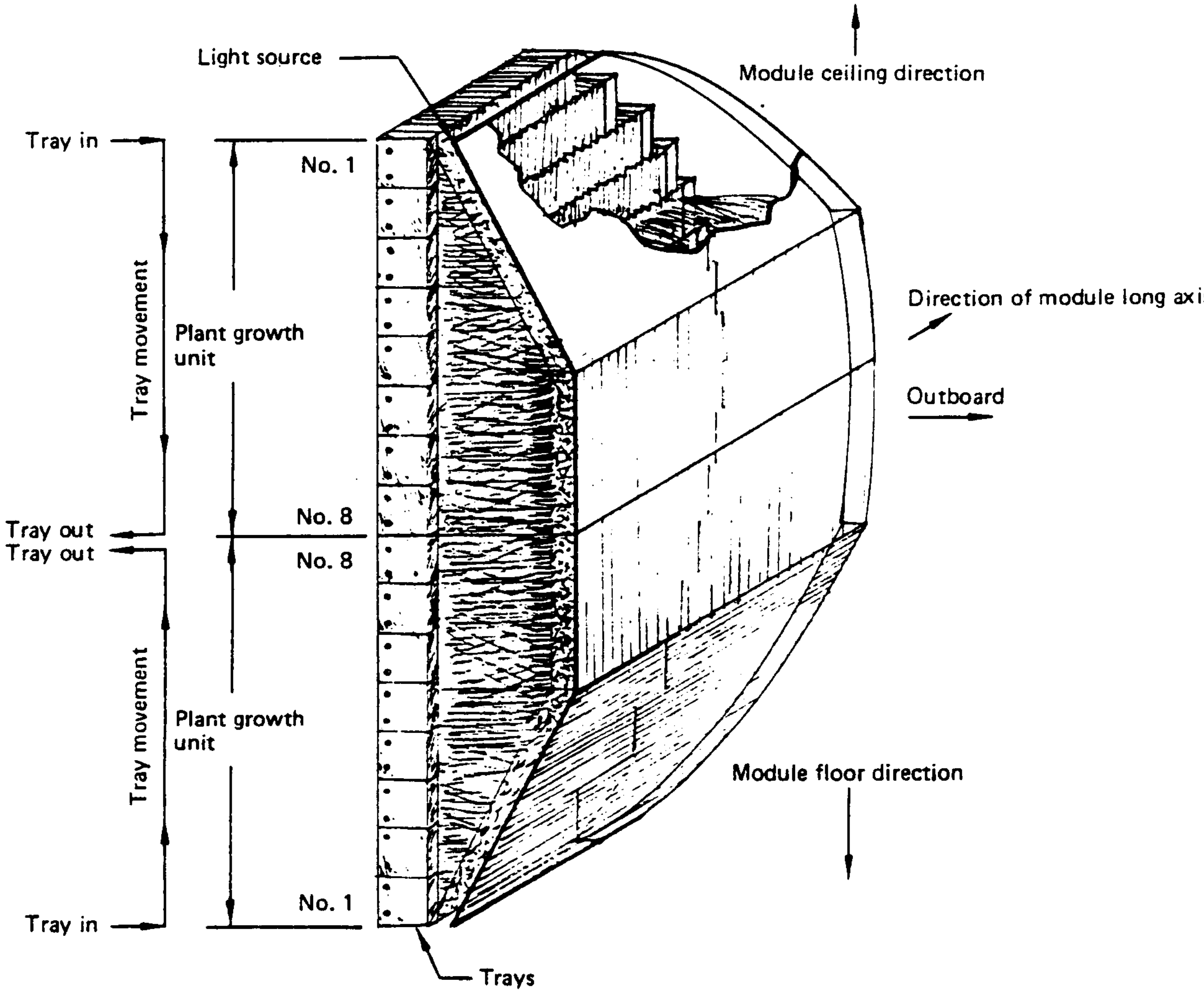

Figure 2.2-1. Tray Positioning in PGU

System	QTY	MASS (kg)	COST (M$)	VOLUME (m3)	PEAK PWR	DUTY CYCLE
Plant growth	24	704.8	22.6	41.2	0	0
Seeder	1	32.8	16.8	.3	.2	7%
Seed cartridges	set	257	2	.3	0	0
Nutrient sup	1	879.9	82.2	1.1	2.2	100%
Atmo ctl sys	1	691	7.4	5.9	6.6	100%
Harvester/proc	1	465.1	49.3	1.3	1.0	5%
Waste regen sys	1	691	74.5	1.2	5.6	14%
Plant lighting	1	6062.8	167.3	8.1	12	66%
Thermal	1	2106.4	24.6	.9	2.4	66%
Robots	set	245.8	73.2	1.4	.3	23%

Table 2.2-1. Plant Growth Unit Summary

2.2.2 Nutrient Supply

The nutrient supply system consists of a main reservoir supply of fresh nutrient solution that supplies each PGU's nutrient system that in turn supplies nutrient solution to each plant growth tray. Sensor probes analyze the nutrient composition, and control replenishment of exhausted ingredients. Periodically, used nutrient solution is dumped to the waste control system and replenished from the main reservoir. Nutrient supply parameters are summarized in table 2.2-1.

2.2.3 Atmosphere Control

The atmosphere control system maintains a constant CELSS air composition, including humidity,and removes contaminants. Plants use carbon dioxide and give off oxygen. Trace contaminants are given off by plants, out-gassing of plastics, the nutrient system, and electromechanical equipment. Air is circulated to the waste management system and contaminants are oxidized or removed by filters. Additional filtering, as required, will be included in the air circulation cooling system. The waste management system supplies carbon dioxide for the plants and nitrogen as required to compensate for leakage. If additional O2, CO2, and N2 are required to maintain an optimum atmosphere, they will be furnished by stored supplies. Atmosphere control system parameters are summarized in table 2.2-1.

2.2.4 Harvesting and Food Processing

The harvester and food processor operate together to separate edible from inedible biomass. Edible biomass is processed to a storable condition then stored. Inedible biomass is shunted to the waste regeneration system. Harvesting and food processing are automated (sec. 2.2.8). A tray of mature plants is placed in the harvest machine, stems are cut and the root biomass is pulled out of the tray. The crop is separated from the waste material and put into storage. Waste materials are ground and stored until the next waste regeneration cycle. Harvester and food processor parameters are summarized in table 2.2-1.

2.2.5 Waste Regeneration System

CELSS waste regeneration system converts organic waste material into constituents needed for plant growth. Organic waste materials are ground into fine particles and

consumed in a SCWO unit. Significant power (5360w) is required for the initial heating of the SCWO unit. Therefore, waste material is collected and stored until there is enough for an efficient burn period. Contaminants in the air are oxidized as air passes through the reactor, which acts as an air contaminant scrubber. Carbon dioxide and nitrogen are gaseous reactor byproducts. These byproducts are used to maintain atmospheric balance. Salts are recovered and used to replenish the plant nutrient solution. Waste regeneration system parameters are summarized in table 2.2-1.

2.2.6 Plant Lighting

Lighting provides the energy source that drives the otherwise closed CELSS system. CELSS lighting system provides high-intensity plant illumination during LEO light-side operations. Reduced intensity illumination is provided during dark-side operations. Sunlight is collected by a solar collector and conducted via fiber optics to the PGU for the primary light source. Artificial light may be provided during the dark-side orbit. At one-tenth of full intensity, artificial light will be provided to conserve power. Fluorescent lights will be used for the artificial light baseline source in this study. Fluorescent bulbs are moderately power efficient and weigh less than the high-intensity discharge (HID) lamp with fiber optic light pipes, which is considered an alternative system. Plant lighting system (solar and fluorescent) parameters are summarized in table 2.2-1.

2.2.7 Thermal Control

CELSS thermal control system provides the means to remove heat generated by electrical equipment, solar illumination, and human activity. The highest heat load is generated during light-side orbit. Conducted sunlight on the plants will bring approximately 81,000 Btu/h into CELSS. If the SCWO is running at the same time, another 50,000 Btu/h or more will be generated. Additional heat will be generated by the fan motors used for air circulation, robot operation, and by other equipment, such as the harvester and nutrient supply equipment. A portion of the heat may be used for Space Station processes requiring heat input. The balance will be dissipated through CELSS and Space Station radiators. Thermal control system parameters are summarized in table 2.2-1.

2.2.8 Robot Operation

CELSS robots are used to relieve crew-time demands. Robots perform routine operations of planting, harvesting, and processing the food crop without human inter-

action. The robotic gardener positions the seeded plant growth tray into the PGU and harvests the tray of mature plants. The food processor robot completes processing the crop through the harvesting equipment. The food processor robot handles tray preparation for reseeding, operates the seeder, and performs limited maintenance tasks. Robotic system parameters are summarized in table 2.2-1.

2.3 PARAMETRIC ANALYSIS

Parametric analyses conducted for this study were used to support preliminary design and sensitivity analysis. Four parameters were evaluated: electrical power, volume, mass, and cost. Initial preliminary designs provided approximate equipment volumes. These volumes were evaluated against CELSS module volume to determine if all systems would fit together. Iterations and refinements to systems design led to a specific set of equipment dimensions. System design was well established by this point, allowing call out of materials, electronics, motors, and other specific items of equipment. These equipment listings are compiled for use in weight estimates.

Weight estimates are conducted using the CELSS systems equipment listings (sec. 4.0). Systems requirements for strength, heat resistance, flexibility, pressures, and other engineering variables are identified. Weights engineers compare these data to existing models with known weights. Some adjustments are made to compensate for unique requirements or operations. The weight of each equipment item is then added to obtain subsystem and/or system totals. Some estimates are made for interconnecting structures, power cables, plumbing, etc. to complete the system weight estimate.

Electrical power requirements were developed for unique equipment by calculating the mass moved, speed at which it moved, and time in operation. Fan, pumps, and other standard-type equipment were assigned values from standard engineering references based on equipment loading. Thermal and atmospheric control equipment power demands are calculated for highest loading. During operations, power demands are expected to be lower because maximum loading is rarely attained. These loading factors are evaluated in section 6.4.

Cost estimates are based on a Boeing parametric cost model (PCM) system in conjunction with the RCA PRICE modeling system. Both systems use equipment breakdowns by mass, power, complexity, technology, manufacturing, testing, and

assembly factors to determine costs. These factors are integrated to determine three cost categories: design and development, manufacturing, and systems integration and checkout. CELSS system costs are the sum of three categories. Launch and on-orbit operational costs are not included in this study.

2.4 SENSITIVITY ANALYSIS

Sensitivity analyses were conducted to identify the key design drivers in developing a CELSS module. These design drivers are -

a. Electrical power consumption.
b. Plant species selection.
c. Internal CELSS module volume.
d. Thermal control.

Design drivers are selected for their CELSS mission impact. This impact is determined by evaluating parametric values for mass, volume, power, and cost. The parameters are then related to edible biomass produced per day per square meter. Relating parameters to crop yield in this manner determines which systems have the greatest impact on the overall CELSS mission to produce food for the crew.

Electrical power has the greatest effect on CELSS design. Electrical power impact is derived from its scarcity on the operational Space Station. About 210 kW are available for the entire station during light-side operations in 1999. Less power is available from station fuel cells during dark-side operations. This power must sustain all station activities, including housekeeping, life support, industrial operations, laboratories, satellite repair, and waste management. Based on current projections, sufficient power will not be available for all of these activities. Allocations will set limits on each module's power consumption. CELSS module designs must conform to these limits. Power limits constrain artificial lighting schemes, especially during dark-side operations. Total artificial lighting at 87.7 kW (table 6.2-4) is an unacceptable design approach. Alternative direct solar lighting designs have serious thermal and safety problems. Solar collectors, using fiber optic light pipes, presented the only viable solution. While providing effective light-side illumination, the solar collector is inoperative during dark-side operations. CELSS design has to provide a low-power lighting system to maintain plants during dark-side operations. Limited electrical power dictates the CELSS illumination system. Thermal control, atmospheric control, PGU, robot, and automation

designs are directly impacted by illumination system selection. Thus, electrical power directly affects the major CELSS systems designs.

Crop selection must be oriented toward maximum edible biomass yield. Three factors combine to determine yield: (1) growth period from planting to harvesting, (2) calories contained in each gram of edible biomass, and (3) edible biomass produced per unit growth area. These factors must be considered in combination when selecting a crop plant. For example, wheat has a 62-day growth cycle, 2400-g/m^2/cycle production rate, and 3.6 cal/g. Wheat can support over three men per 35-ft long by 14-ft diameter module. Mixing crops to balance nutrition must consider the impact low productivity has on size, power, mass, and cost for CELSS designs.

Internal module volume limits the area that can be dedicated to crop production. Each CELSS module requires a certain amount of overhead equipment for atmosphere and temperature control, waste management, nutrient supply, and food processing and storage. The remaining internal volume is used for PGUs. CELSS design task is to minimize overhead penalty while increasing quantity of operational PGUs. Future CELSS designs should consider advantages derived from larger modules. PGUs can be added at little additional overhead penalty once the initial support equipment penalty is paid. This requires increased module size either through greater length and/or diameter. Increasing number of PGUs by adding small modules results in paying the full overhead penalty each time.

Intense plant illumination generates heavy heat loads within the CELSS module. Illuminating heat sources are located directly over plants. Preventing crop heat damage requires a powerful, redundant, and integrated thermal control system. Thermal designs incorporate atmospheric control to transport heat from plants to heat exchangers. PGU designs were altered to aid in effectively removing heat. Waste management systems are designed to incorporate high-efficiency liquid cooling systems. Even the robot was slowed down to reduce heat loads generated by larger motors required for higher speeds. All CELSS systems were designed to reduce thermal load, thereby reducing size and power demand for the thermal control system.

2.5 RESEARCH AREA SUMMARY

Three classes of research areas were identified in this study: biology, engineering, and advanced technology. Biological research areas address the issue of growing plants in a

microgravity environment. An example is plant tropism. Engineering research areas address the questions of designing and constructing a CELSS facility. An example is development of structures that do not contain phytotoxic off-gassing materials and are able to withstand corrosive nutrient solutions. Advance technology research areas address the equipment and capability that will be needed, but does not exist, to support a CELSS facility in micro-gravity. An example is development of a fiber optic solar ray collector that will function in a space vacuum and direct solar radiation.

Key research areas are identified in the following listing. These areas are selected from the listing in section 7.0, which contains additional research area topics. This larger listing identifies CELSS systems and parametric values affected by the research area.

2.5.1 Biological Research Areas

The following are certain biological research areas that need immediate attention to support further CELSS development.

a. Determine microgravity-grown plant dimensions. These dimensions impact sizing PGUs, which consume the greatest percentage of volume in CELSS module.

b. Determine edible biomass production per unit area when grown in a microgravity environment. Even minor changes in production can create major increase or decrease in plant growth volume required per man.

c. Determine which organisms (e.g., algae, bacteria, fungi) can convert inedible plant biomass to edible food stocks for humans. Recovering normally inedible biomass can reduce both volume and energy requirements to feed each crew person.

d. Determine plant development under light- and dark-orbit cycles. Illuminating plants only during Space Station light-side orbit reduces electrical power and equipment requirements. Questions exist as to plants viability, growth characteristics, reproduction, and food production rate under the Space Stations 60-min light 30-min dark cycle.

e. Determine lowest illumination levels that maintain plant photosynthetic state. This information supports low intensity, artificial lighting design for Space Station dark-orbit phase. Using low-level illumination to hold plants in photoactive state may

support high production levels while significantly reducing electrical load on the Space Station.

f. Determine lighting characteristics necessary to induce phototropic response in plants. Inducing plants to grow in a predetermined direction using light is the least difficult tropistic response option. Alternative growth orientation procedures (e.g., electrical fields, chemical sprays, agitation, etc.) all add utility penalties and complexity to CELSS design.

g. Identify high-yield plants that are adaptable to growth in CELSS. Pursue selective breeding and/or genetic engineering to develop plants for high yields, compact size, and rapid maturity. Plant species in which all, or most, of the plant is edible are especially valuable.

2.5.2 Engineering Research Areas

a. Develop PGU design using noncorrosive and nonphytotoxic material while maintaining lightweight structure. A highly corrosive nutrient solution and problems with off-gassing in a closed module require careful material selection. High launch costs dictate that PGU mass be minimized.

b. Design nutrient fluid handling system that ensures adequate supply, constant monitoring, and prevents leaks.

c. Design plant processing unit that can process a variety of edible foods. This unit must separate inedible from edible biomass. It should have the capability to wash, dry, and sort edible plant products as required. Plant processing unit will store edible materials and grind inedible material for regeneration.

d. Design robotic gardener to use multiple, specialized tools for plant maintenance and processing. Robotic gardener is a key element in CELSS automation plan. With this robot, one crew member (on a part-time schedule) can support many additional crew members. This unit eliminates human requirements during routine CELSS operations. Human involvement is limited to equipment maintenance and repair and picking up the harvest for consumption.

2.5.3 Advanced Technology Research Areas

a. Develop solar light collection system to provide plant illumination. A lens or mirror system focusing sunlight on fiber optic cables provides an option for conducting sunlight into plant growth area. Cable construction, rotating joints, terminal illuminators, and collector pointing all require development.

b. Design SCWO system for use in a microgravity environment. This unit requires a salt separation unit added to recover plant nutrients. Recovering nutrients and releasing carbon and water from waste materials are essential processes in CELSS. SCWO prototypes have demonstrated a potential to accomplish these goals with a small energy-efficient system.

c. Develop physiochemical or biologically based inedible-to-edible biomass conversion systems to maximize return from each plant grown. Low-energy systems are preferred even if they require slightly larger volumes and masses. Biological system must adapt to varying waste types and quantities. Physiochemical system should not require resupply from Earth or hazardous materials.

d. Develop mercury free, low temperature, high-intensity discharge (HID) lamps. These lamps are inherently more efficient than other artificial light sources. However, their high temperature precludes spacing close to growing plants. Mercury amalgams are contained in these lamps, which produce a hazardous material handling problem. The problem is compounded by the closed-environment system.

3.0 CELSS CONCEPTUAL DESIGN

3.1 CONCEPTUAL DESIGN PHILOSOPHY

The purpose of this study was was to develop design options for higher plant growth systems for use on Space Station. These designs are for growing wheat, soybeans, and potatoes in a micro-gravity environment. A CELSS module is scheduled initially to be a research tool attached to the Space Station. Essentially, the total system will recycle water, atmosphere, and plant nutrient material.

CELSS conceptual designs developed for this study are intended to define a closed microgravity higher plant growing system. An optimum design was developed within volume and power constraints of Space Station. The requirement for very limited human operational involvement dictates a highly automated system.

Designs developed for this study are based on existing technology in electronics, automation, robotics, and biology. All systems that received serious consideration are accommodating to automated servicing. Routine maintenance and repair times are planned to be minimized by the use of fault-tolerant systems and/or high-reliability parts. Only unplanned repairs and maintenance are expected to be performed by crew members.

3.2 CONCEPTUAL DESIGN EVALUATION

PGUs comprise the largest single unit in CELSS module design. Since many PGUs are contained in each CELSS module they heavily impact volume utilization. Designs were examined and rated in terms of useful volume, efficiency of light distribution, reliability of mechanical systems, ease of service, ease of harvest, cost, etc. Figure 3.2-1 is an example of a rating sheet. Major rating criteria for CELSS systems conceptual design are -

a. Minimize human involvement in CELSS.
b. Use Space Station common module primary structure.
c. Satisfy caloric requirements for two crew members.
d. Satisfy biological requirements for plants.

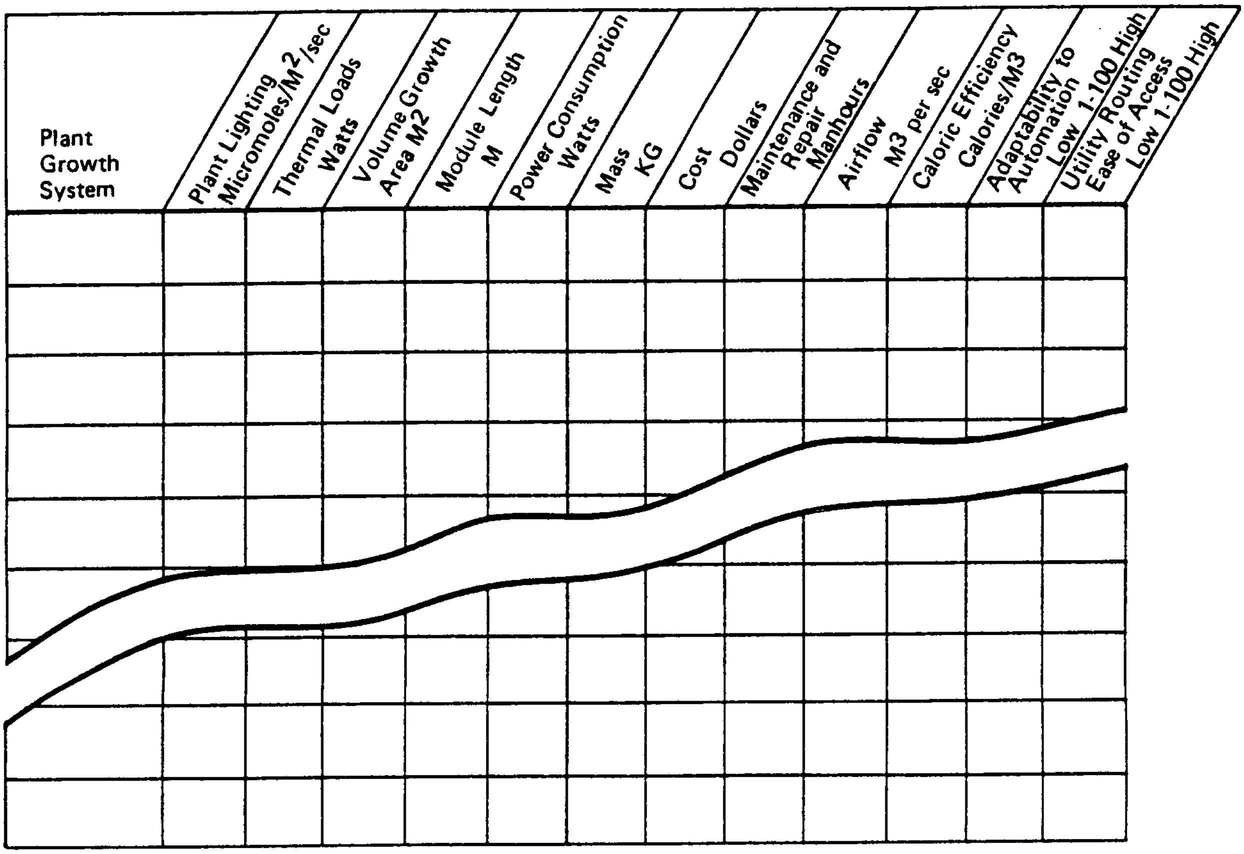

Figure 3.2-1. Conceptual Design Selection by Comparison of Design Criteria Rating Sheet

Because crew time is a critical resource, human involvement in CELSS must be kept to a minimum. This drives design to highly autonomous systems for a broad range of operations. CELSS systems are only planned to require human attention when equipment failure or severe plant damage occurs.

Eleven different PGUs were considered. Brief descriptions of each of these units follow.

a. Conveyor-belt PGU (fig. 3.2-2), uses two conveyors facing a common light source. Newly seeded trays are inserted at shallow side (where lights are close to conveyor). Plants grow as conveyor belt slowly moves. Deep side (where lights are far away from conveyor) has mature plants. These are removed from conveyor for harvesting.

b. Honeycomb tray concept (fig. 3.2-3) has six-sided trays facing toward six-sided light sources. Plants grow on two or three sides depending on tray location in pattern. Trays plug in longitudinally to growth unit.

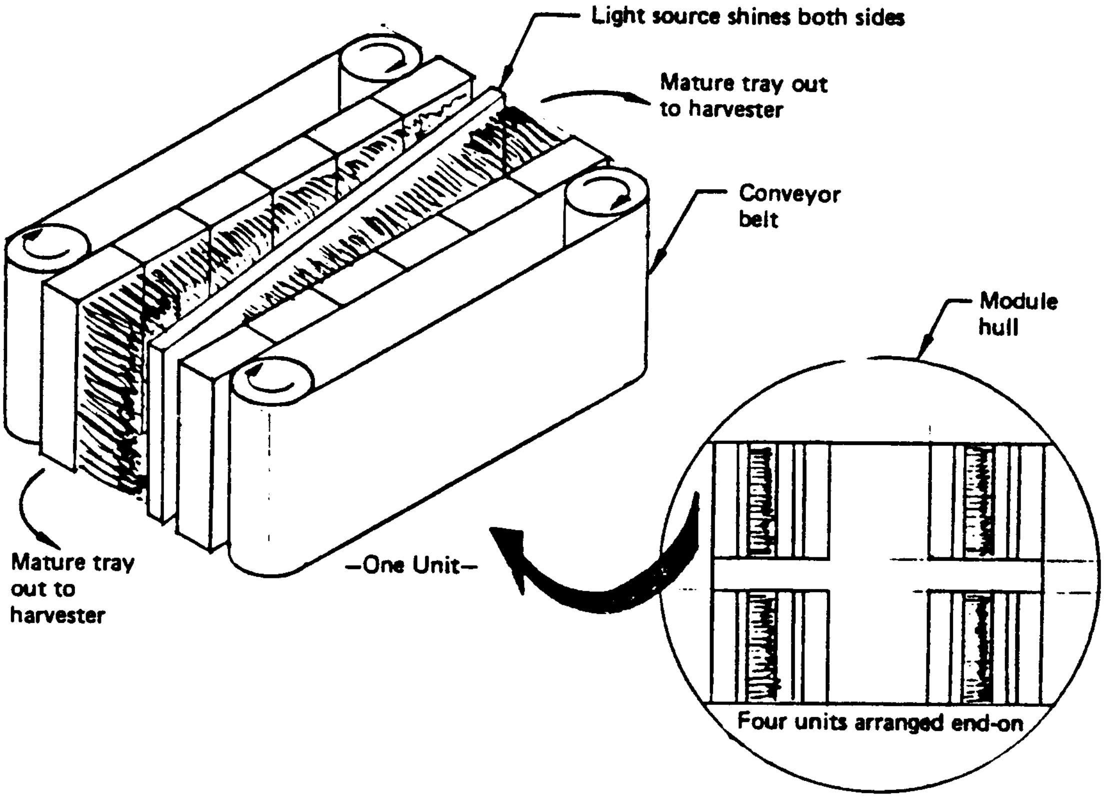

Figure 3.2-2. Conveyor Belt PGU

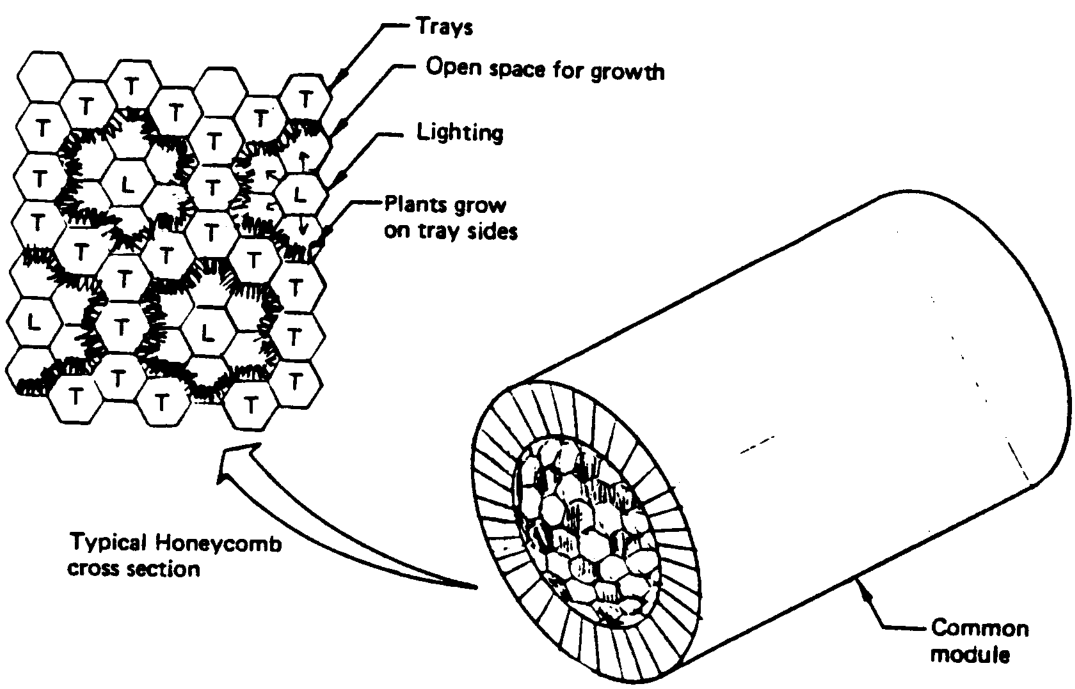

Figure 3.2-3. Honeycomb Tray Concept

c. Parallel-to-hull concept (fig. 3.2-4) grows plants in a false wall between module interior and hull. False walls permit module interior use for other purposes. The robot travels against hull, is short and long, and carries harvester with it.

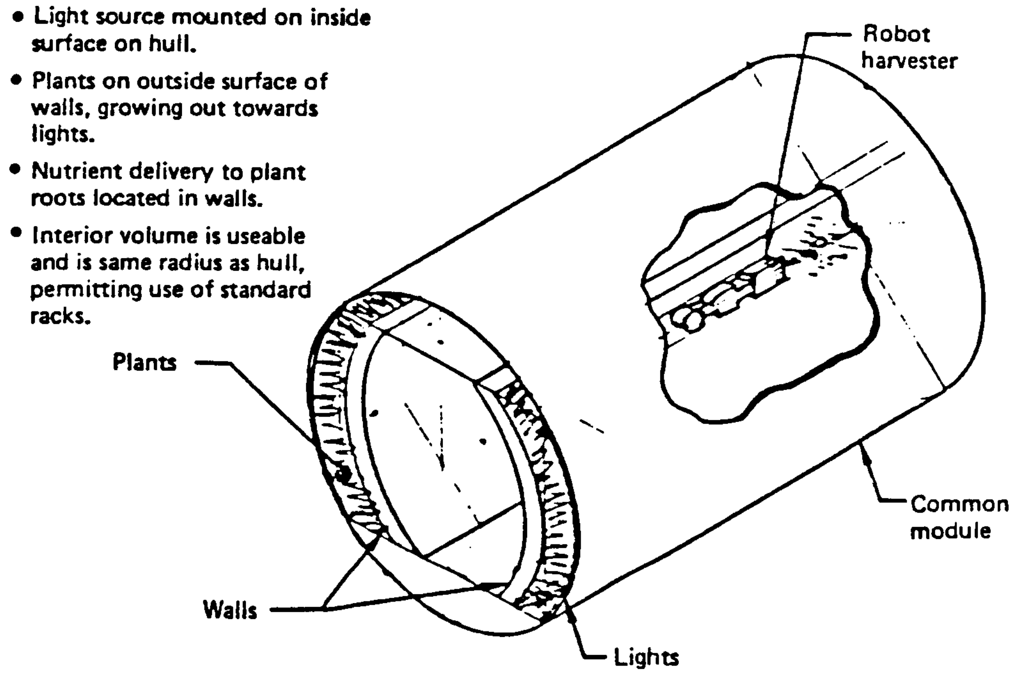

Figure 3.2-4. Parallel to Hull Concept

d. Warehouse tray stack (fig. 3.2-5) has trays on vertical racks serviced by a robot that moves along center aisle. Trays fit into different sized slots, which places lights as close as possible to plant canopy while allowing area for growth. As plants grow, robot moves trays into progressively larger slots that accommodate growth.

e. Cone-shaped growth chamber (fig. 3.2-6) has a continuous tray moving through a cone with light source facing inward from cone surface. Growth surface is a collapsible continuous tube. Slit in tube allows injection of nutrient and removal of roots at harvest.

f. Radial tray concept (fig. 3.2-7) places trays facing outward from the module center with the robot at the module center. Circumferential arrangement of trays uses large available surface area for plant growth.

g. Baloney slice concept (fig. 3.2-8) has vertical panels that grow plants on their sides. As plants grow, panels move laterally to allow growth and adjust lighting distance from plant canopy. Panels are removed from the system for harvest.

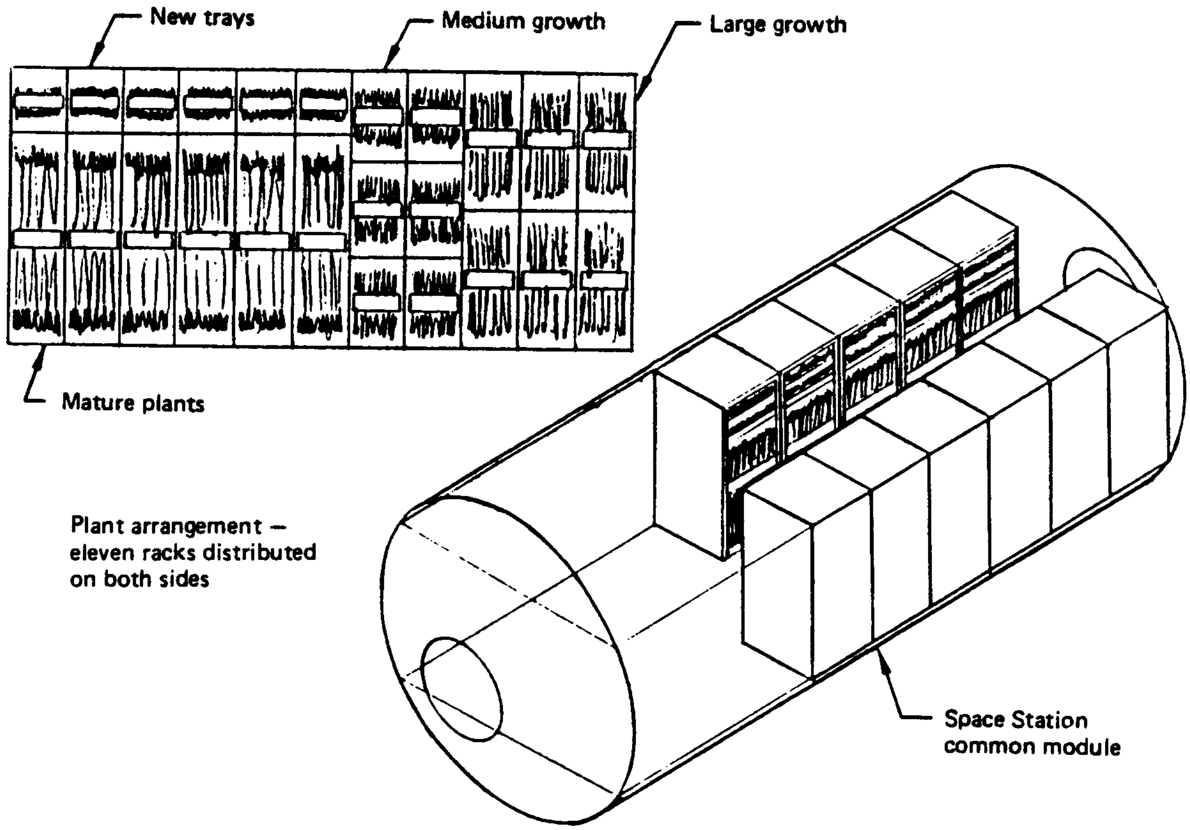

Figure 3.2-5. Warehouse Tray Stack

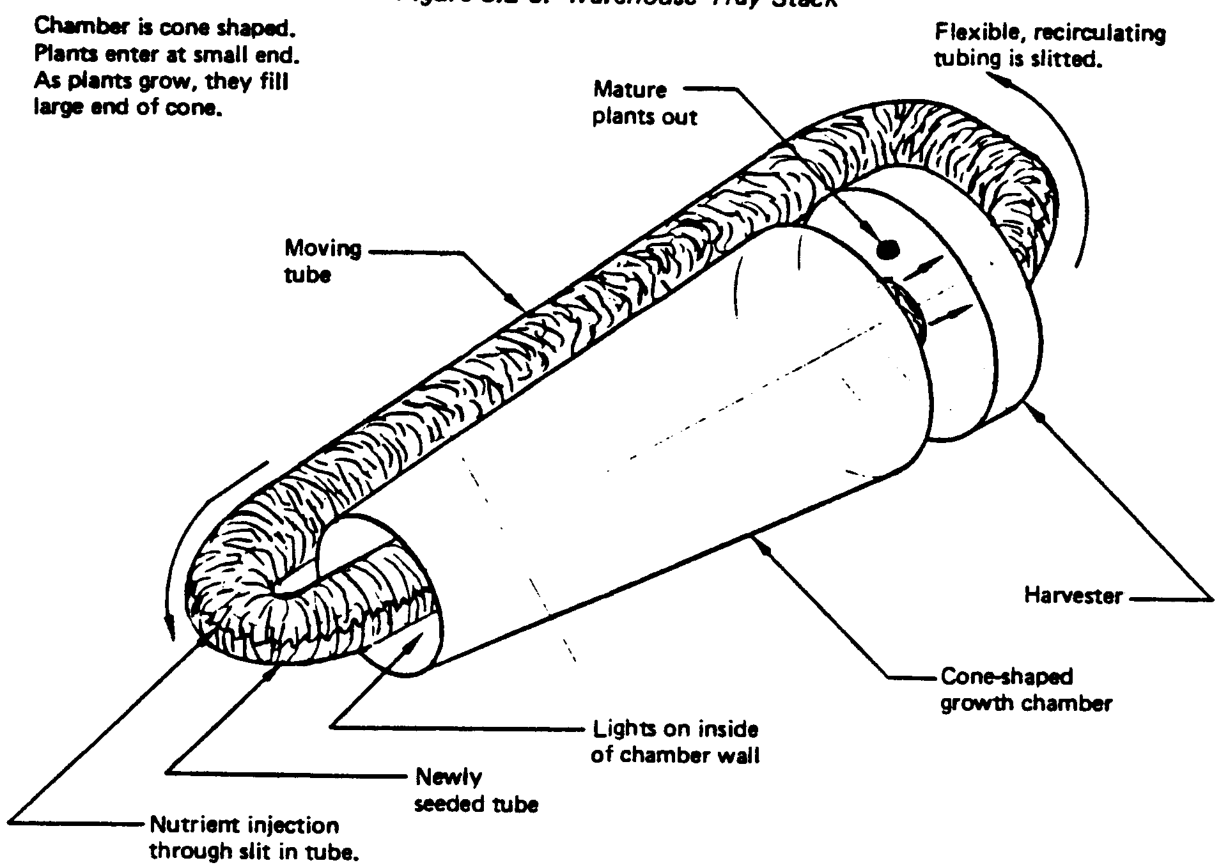

Figure 3.2-6. Cone Shaped Growth Chamber

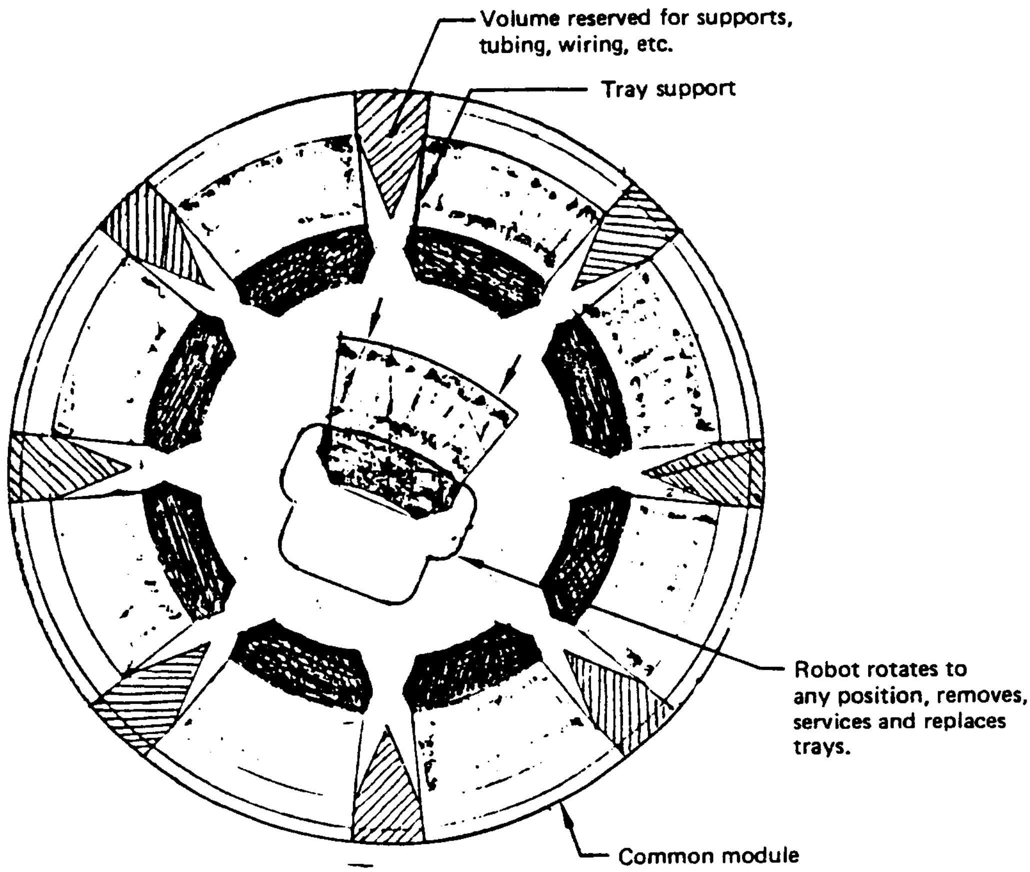

Figure 3.2-7. Radial Tray Concept

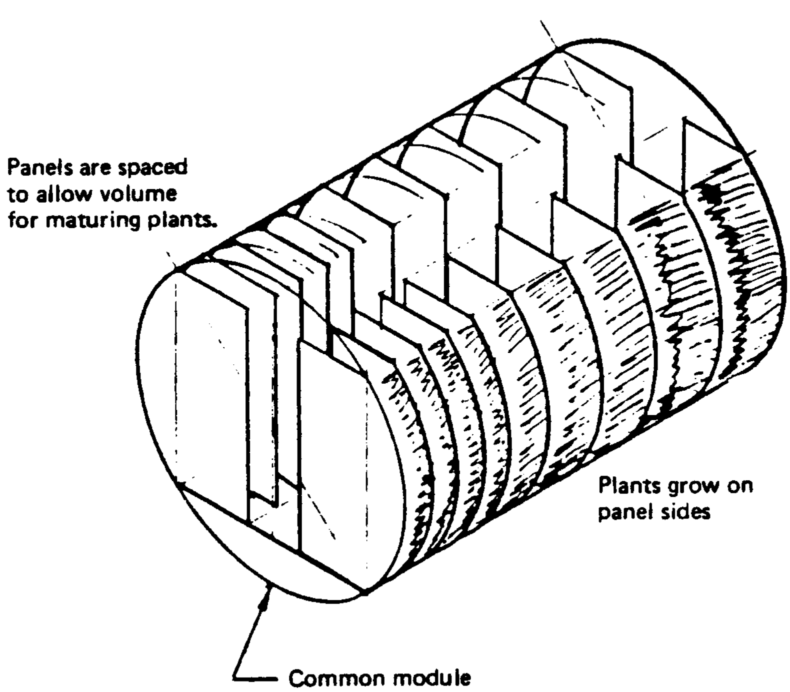

Figure 3.2-8. Baloney Slice Concept

h. Clamshell growth concept (fig. 3.2-9) grows plants on a core facing toward the inside of a sphere that has a light source. Plants grow on most of the core excluding only the tube that supports core and provides nutrient plumbing.

i. Rotating drum concept (fig. 3.2-10) has a slowly rotating drum (one revolution per growth cycle of 60 to 115 days). Seeding and harvesting are performed continuously as the drum rotates.

j. Hybrid tray stack (fig. 3.2-11) has trays on vertical racks accessible from an aisle. The racks extend from aisle to module inner hull surface. This creates progressively deeper slots with deepest slot at module center line. Trays are built with accordion folds so they may be collapsed to fit the shallow top slot. The trays are moved to deeper slots as plants mature. This allows the tray to be expanded, thereby providing more plant growth area per tray. Trays are moved from slot to slot and finally to the harvester by robot.

k. Accordion tray stack (fig. 3.2-12) has expanding trays in a vertical stack with plants growing on the sides. This unit was selected as the best CELSS PGU concept. It

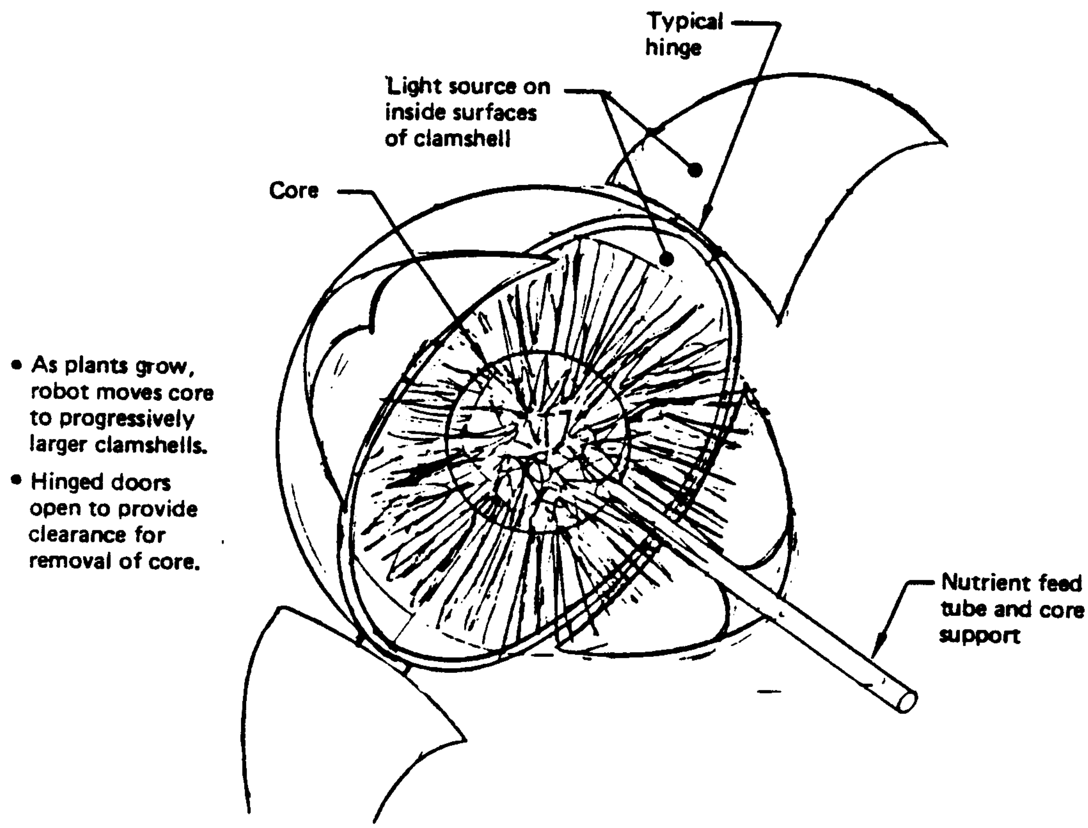

Figure 3.2-9. Clamshell Growth Concept

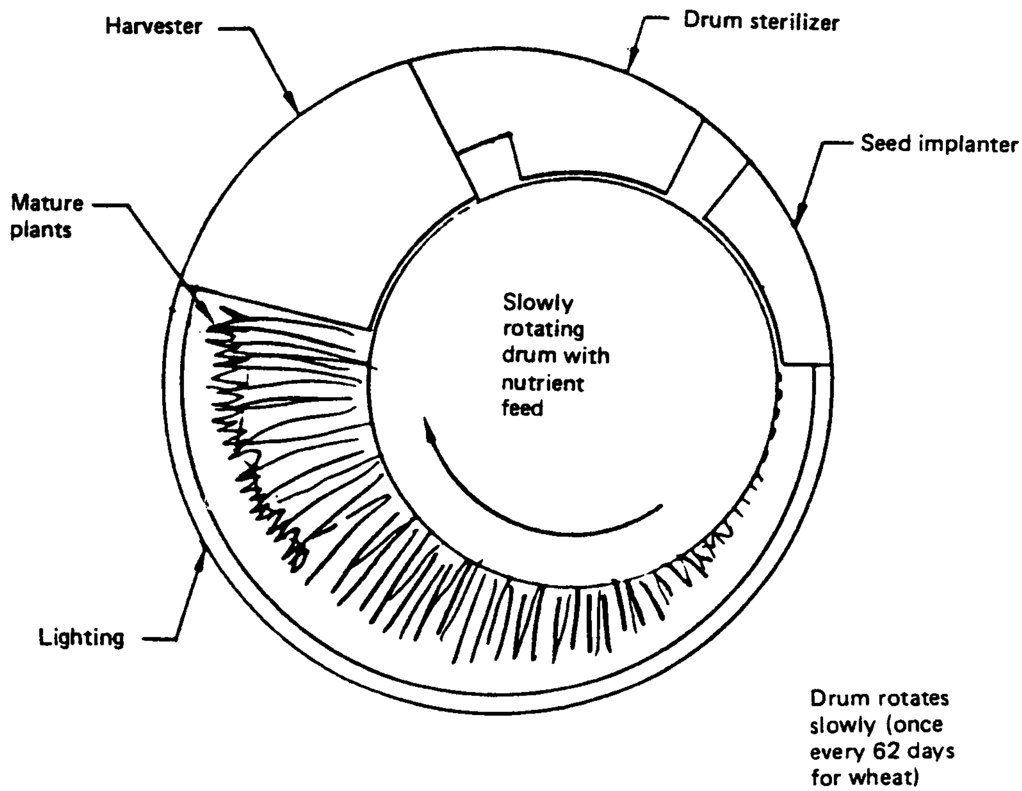

Figure 3.2-10. Rotating Drum Concept

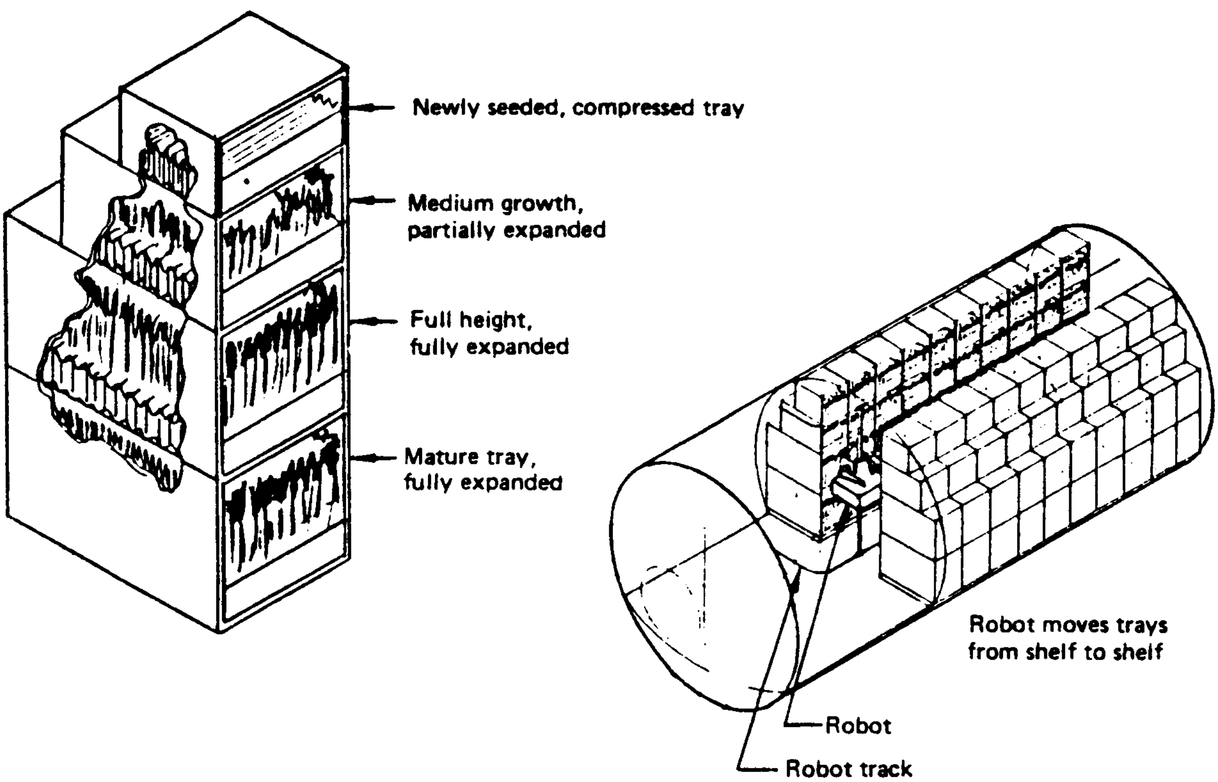

Figure 3.2-11. Hybrid Tray Stack Concept

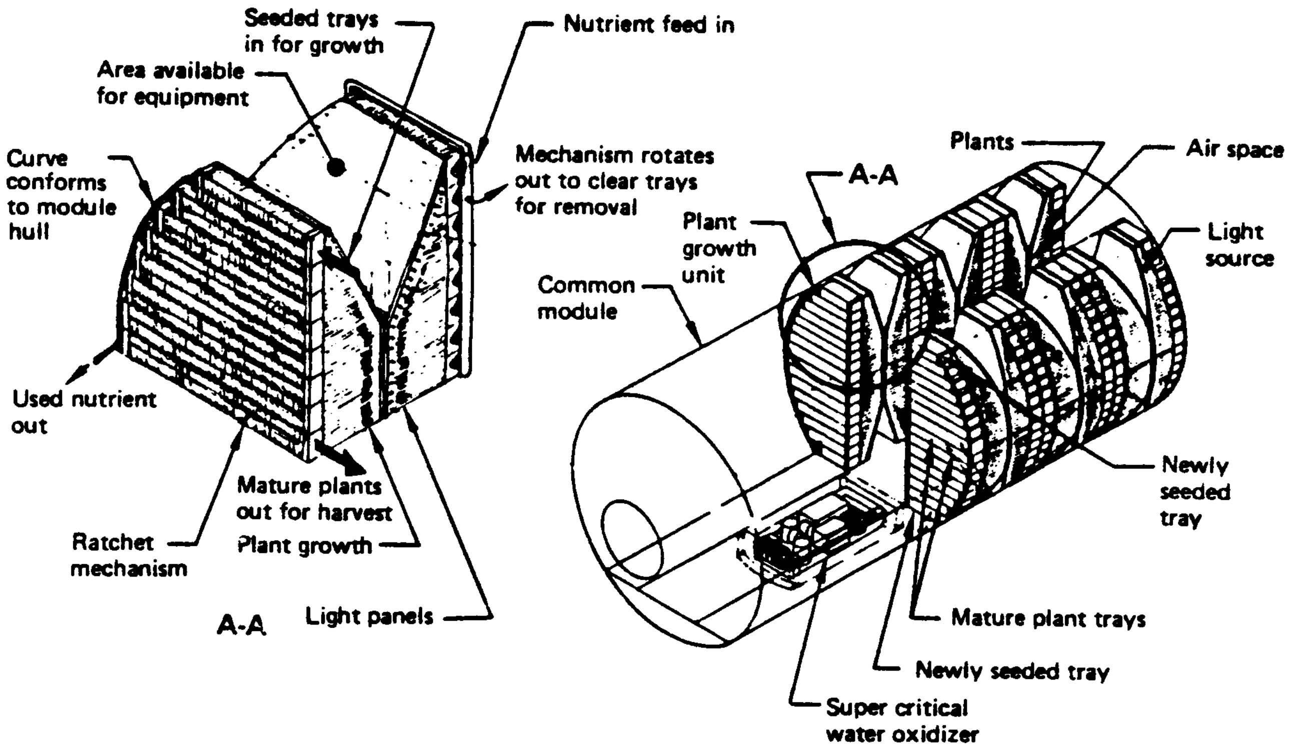

Figure 3.2-12. Accordian Tray Concept

required minimal volume while supporting maximum lighting efficiency and reliable mechanisms.

3.3 CONCEPTUAL DESIGN SELECTION PROCESS

CELSS study employed a design process that compared design criteria analytically to identify best-fit conceptual designs. This process used a series of design iterations, criteria refinements, and design reviews. Process results are designs that satisfy CELSS requirements.

During the CELSS study, criteria weighting (importance) changed as design options were explored. For example, mechanical complexity was not initially considered a major design driver. However, crew time is a major design driver. Therefore, CELSS was substantially automated to minimize human interfacing with CELSS. Initial designs tended to be mechanically complex PGUs. Evaluation revealed these mechanically complex designs decreased reliability, which increased crew maintenance and repair time. While some mechanical complexity is unavoidable, it is necessary to simplify systems designs to reduce crew maintenance and repair load. During design iteration, mechanically complex components were eliminated, if possible.

It was also determined that systems could be designed that were adaptable to changes in requirements. An example of this is the PGU. The ground rules were to grow wheat, soybeans, and potatoes. Initial conceptual designs concentrated on sizing for wheat growth. After the first selection of growth systems to accommodate wheat, sizing for soybeans and potatoes were considered. PGUs that were unadaptable to changed requirements were eliminated. PGUs that did meet increased requirements did so because of their inherent flexibility. These designs can be changed yet again to accommodate new requirements. This design flexibility is useful for further development. As future CELSS development occurs, the selected PGU should be capable of changing to meet most new plant growth requirements.

Three configurations emerged from the selection process as final candidate concepts. Selected concepts were (1) warehouse tray stack, (2) accordion tray stack, and (3) hybrid tray stack. These concepts best satisfied design issue requirements. Suitability determination was made by comparing concepts against individual issues and ranking accordingly.

3.3.1 Warehouse Tray Concept

This concept configures growth trays to fit into graduated height openings in a vertical stack (fig. 3.2-5). Nutrient is supplied by pressure-fed injectors. A vacuum system removes excess and spent nutrients. When a tray is removed, nutrient and vacuum systems are disconnected. Valve arrangement prevents leakage.

Lighting panels are located above openings in stack. This distributes light on a tray-by-tray basis and allows regulation of light intensity for different growth phases.

As plants grow, trays are removed from their slots and transferred by a robot to taller slots that can accommodate taller plants in the next phase of growth. This happens incrementally until a given tray has been placed in a slot where the plant matures. At maturity, the tray is removed entirely from the stack and transferred to harvesting equipment.

After harvest and tray recondition, the trays are reseeded and placed in the smallest size slots in vertical stack so growth process can be repeated.

The warehouse tray concept is conventional in construction. It can be built of simple-angle shapes attached by mechanical fasteners. No mechanisms are required within the structure for tray manipulation, the robot performs these functions.

The warehouse tray stack does not optimize volume usage. Area between racks and hull is not used for plant growth. Light distribution is not optimal. Seeds are spaced for mature plant spacing requirements. Until plant canopies cover the tray surfaces, light reaches the tray surface and creates undesirable heat.

3.3.2 Accordion Tray Concept

The concept (fig. 3.2-12) is centered around use of trays that are accordion pleated so they expand longitudinally. Trays are essentially rectilinear in section and expand from approximately 36 to 60 in. Tray ends are removable for harvesting operations. This allows robot access to tray interior to push out root masses.

The trays are arranged (fig. 3.2-12 A-A) so that plants grow out one or both sides. Trays are stacked vertically, one tray abutting the other. They are pushed down incrementally and expanded by a mechanism that can be either a tracked device or a tray-mounted ratchet.

Each time trays are moved down incrementally, the nutrient delivery system disconnects and moves clear of the tray travel envelope. When trays are repositioned, nutrient injectors are returned to engage tray nutrient delivery orifices. Nutrient leakage is prevented by an automatic valve system that requires firm seating of nozzles before fluid transfer. Tubing inside trays carries nutrient to multiple misting nozzles that spray nutrient directly onto roots. A vacuum pickup system collects spent and excess nutrients for recycling. Tubes inside trays collect nutrient, transferring it through exhaust nozzles similar to nutrient injectors.

The bottom trays contain the most mature plants. The tray is removed from the PGU stack, making room for the remaining trays to move down into the next growth position. The tray containing mature plants (which is fully expanded) is transferred to the harvesting area.

Harvesting equipment cuts and removes roots from the tray interior, permitting the remainder of the plant to be pulled out and processed. The tray is then sterilized and

reseeded. After reconditioning and reseeding, the tray is compressed and inserted at the top of the PGU stack to repeat growth process.

The accordion tray stack uses volume efficiently. It expands to follow module hull contours as plants grow. A smaller lighting system can be used in early stages of growth. The accordion tray stack permits greater concentration of light onto plants because plants are spaced closer when younger and move apart as they grow.

3.3.3 Hybrid Tray Concept

The hybrid tray concept involves trays that have a vertical orientation similar to the warehouse concept but expand on one axis. This means newly seeded trays can go into openings more shallow than mature trays. Again, as plants grow, hybrid trays are expanded and moved to larger openings in vertical stack (fig. 3.2-11).

The hybrid tray concept improves volume usage over the warehouse tray, but not as well as the accordion tray. Improvements in lighting efficiency are similar.

These concepts were submitted to NASA for review and final selection process. The accordion stack tray concept was selected by NASA for further development during study preliminary design.

3.4 CELSS SUPPORT SYSTEM

The accordion stack tray concept selection provides the base from which the remainder of the support systems designs can be considered. CELSS support systems are -

a. Food harvesting, processing and storage.
b. Seeding equipment.
c. Robot.
d. Thermal control system.
e. Atmosphere control system.
f. Plant lighting.
g. Waste regeneration system.
h. Nutrient supply system.

The support systems design philosophy is to optimize for volume and conserve Space Station resources. Highly reliable mechanical systems are preferred. Systems that accommodate automation are preferred to reduce human workloads. Module shell cost optimization is accomplished by using baseline Space Station common module primary structure.

3.4.1 Harvesting, Processing, and Storage

The harvesting, processing, and storage system was developed to ensure compatibility between PGU, tray design, robot, and a series of design iterations to the PGU and harvester. The resulting harvester concept has capability to harvest wheat, soybeans, and potatoes. It will separate edible biomass (crop) from plant and root masses. The attached food processing system will wash or dry crops as needed for storage. The food processing equipment is fully automated processing plant products from harvest to storage. Volume occupied by harvester is approximately one standard Space Station equipment rack, filled from floor to ceiling.

3.4.2 Seeder

The automated CELSS tray seeder operates in conjunction with a robot to apply a seed-embedded foam tape over slots in an accordion tray surface. The seed tape seals tray slots to prevent nutrient leakage. The seeder uses a ridged roller to press tape firmly into the tray pleated surface to ensure adhesion. A solenoid-activated knife cuts the seed tape. Clearance is provided behind tape applicator mechanism for tray length.

The seeds are stored on tape contained in a cartridge. Unused tape remains in the cartridge, protected against humidity and temperatures that could cause seed deterioration. The robot can remove tape cartridges from seeder, store them, and load different seed tape cartridges into seeder. This allows use of a common seeder for all plants.

3.4.3 Robot

The CELSS system concept includes robots, which are autonomous for normal operations. The robots have the capability of handling plant trays through the entire growth process, from seeding to harvesting. The robots notify the crew of equipment failure or plant damage. (See sec. 3.4.8 for a description of the proposed robot function.) A power conservation concept limits the robot cycle times to light-side orbit. For example, a

plant tray can be harvested and processed in one sunlit segment of an orbit. CELSS generates approximately four trays per day. There are 16 orbits per day, the robot will use one-forth of its time to harvest trays, the remaining time can be used for monitoring, maintenance, and inspection tasks.

3.4.4 Thermal Control System

The thermal control system uses air flow around plants and over light sources to collect heat. This heated air passes through a heat exchanger connected to the Space Station thermal bus. Selected high-heat sources, such as the waste regeneration system and HID lamps, use liquid cooling loops to achieve greater efficiency. Liquid cooling also connects to the Space Station thermal bus.

3.4.5 Atmosphere Control System

The atmosphere control system uses the Space Station as a reserve and buffer system for CELSS. Carbon dioxide is collected from the Space Station ECLSS system and piped to CELSS. It is released as needed to maintain desired carbon dioxide partial pressure. The oxygen generated by plants is collected by CELSS environmental control system (ECS) and piped to Space Station or reserve tanks. Stored oxygen may be used later to supply the waste regeneration system or dark period plant respiration as well as crew needs. Nitrogen is used as atmosphere inert gas. It is drawn from Space Station storage tanks to makeup for leakage. Water vapor is condensed and piped to the nutrient supply system for makeup water.

The atmospheric contaminant control system uses filters, catalytic afterburners, and waste regeneration system. A percentage of each air exchange is passed through filters and afterburners, depending on contaminant level.

3.4.6 Plant Lighting System

The plant lighting system provides plant illumination requirements for normal plant development and accelerated growth. A full intensity (750 to 1000 $\mu mol/m^2/s$) plant lighting can be provided during light-side orbital periods using either fiber optic solar light collectors or artificial lamps powered by the Space Station electrical power. Space Station photovoltaic power sources will charge electrical power storage devices for use during dark-side orbital periods. This study uses estimates that suggest that approxi-

mately one-tenth intensity maintains plants in a photosynthetic state during dark-side orbital periods. This is provided by artificial light using Space Station-stored electrical power.

3.4.7 Waste Regeneration System

The CELSS waste regeneration concept uses the SCWO system. This system was selected by NASA for its potential increased efficiency obtained by operating at elevated temperature and pressure. Short duty cycles are used to reduce power consumption especially during dark-side orbital periods. Waste heat from the SCWO exothermic reaction is used to preheat wastes thereby reducing power requirements. A salt separation system is envisioned to recover nutrient salts for reuse. Carbon dioxide and water vapor given off are collected and stored for later use.

3.4.8 Nutrient Supply System

The nutrient supply system uses eccentric cam-mounted injectors that seat against openings in tray ends. The injectors have o-rings seats to form a leak-resistant seal when they are inserted into mated receptacles in each growth tray. Each tray has a probe that permits the injectors to operate only when fully inserted and sealed. The spray nozzles are located inside the trays to carry nutrient to plant roots. When the injectors are retracted, the injector valve closes, stopping nutrient flow. A valve at the tray opening closes to prevent any incidental nutrient leakage from tray. This concept does not require any threaded fittings, only accurate alignment of the injector and tray. This nutrient supply concept was developed to allow a robot to readily perform tray change-out.

Nutrient maintenance and contaminant control uses a dual-reservoir concept. One reservoir contains a generic nutrient solution made from salts and water recovered in the waste regeneration system. A second reservoir is located on each bank of PGUs and includes monitoring devices and injection systems to keep nutrient pH, conductivity, nutrient content, and oxygen level within specified parameters. Additional injectors may be used for pathogen control or chemical stimulation. This concept calls for periodic nutrient dumping to the waste regeneration system, a precaution against phytotoxic material buildup in the nutrient solution. Each PGU bank has a separate nutrient supply system to aid in preventing disease spread.

3.5 STUDY GUIDELINES

NASA Ames Research Center provided or approved assumptions and guidelines for conducting this study. These guidelines provide a baseline from which to compare and evaluate various designs. CELSS study guidelines are as follows:

a. Design CELSS module to grow edible biomass to provide the caloric contents for two men per day.

b. Primary crop will be spring wheat (Triticum aestivum - Ultra-dwarf)

c. Secondary crops will be white potatoes (Solanum tuberosum -norland) and soybean (Glycine max - Ransom)

d. Aeroponics will be used for wheat and soybean growth. A modified hydroponics system will be used for potatoes.

e. PGUs will be open to the module atmosphere.

f. Cabin atmosphere carbon dioxide range will be controlled at 250 ppm to 2000 ppm (+/- 20ppm).

g. Cabin humidity range will be controlled at 40% to 85% (+/-5%) relative humidity.

h. PGU plant canopy temperatures will be individually controlled using airflow injection.

i. SCWO system will be used for waste regeneration. Technology will exist for separation of by-products into salts usable in nutrient solution.

j. Module size will be compatible with the Space Shuttle (STS). The module contents will be assembled on orbit.

k. Module equipment must be repairable and/or replaceable on orbit.

l. The CELSS module will be totally automated for plant seeding, growth, harvesting, and processing for storage.

m. No centrifuge will be incorporated in the CELSS module design.

n. Collect CO_2 from Space Station and return excess O_2 to Space Station.

o. Urine, hygiene and process grey water will be fed to SCWO for use as makeup water.

p. Oxygen supply for humans in CELSS module will be provided by plants or ducted in from Space Station.

q. A continuous-harvesting approach will be used for PGU design.

r. Plant lighting levels will be adjustable for dark and light cycles.

3.6 CELSS STUDY ASSUMPTIONS

CELSS study assumptions are -

a. Wheat, potatoes, and soybeans will grow and reproduce in a micro-gravity environment without the aid of artificial gravity.

b. Transpired water from higher plants is considered potable with limited posttreatment.

c. Higher plants grow to the same general dimensions in micro-gravity as on Earth.

d. Plants will grow with 300 $\mu mol/m^2/s$ illumination intensity.

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4.0 PRELIMINARY DESIGN

CELSS preliminary designs are developed from study conceptual designs and are reported in this section. Preliminary design focused on developing a volume efficient, low-power CELSS system from NASA selected conceptual design. Plant growth support systems are selected to provide the best volume and power utilization while keeping costs and manpower requirements to a minimum. Plant illumination systems are the preliminary design variable that will be evaluated during sensitivity analysis. Preliminary design also included integration tradeoff analysis between candidate systems.

The conceptual design selection process resulted in the accordion tray plant growth concept selection by NASA as the basis for preliminary design. This PGU concept was modified to use several natural and/or artificial lighting system combinations. An accordion tray system using a solar collector augmented with fluorescent for dark-side orbit illumination was selected as the best compromise CELSS system from the options evaluated.

The following ground rules and assumptions were used to select systems.

a. Design for enclosure in the Boeing-proposed phase B Space Station common module.
b. Design to function in microgravity$<10^{-3}$g.
c. Adaptable to function in reduced gravity (10^{-2}g to 0.9g).
d. Design for operation with automated systems, including robots performing routine activities. CELSS will be manned only for nonroutine maintenance and repair functions, and to transport food to the Space Station galley.

4.1 CELSS SYSTEMS DEFINITIONS

The systems making up a CELSS module perform the functions necessary to grow a food crop (wheat etc.) in the Space Station environment. The performance requirements for each system are described in the following sections.

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4.1.1 Plant Growth Unit

The PGU provides a place for growing plants and a means to hold them in position during the growth cycle. The method of retaining and holding the plants permits exposure to light and nutrients. PGU design must confine nutrients to root zone.

The PGU design provides a means of starting the plants from seed. Mature plants can be automatically collected for food processing. PGU design permits sequencing of crop planting and harvesting in order to have daily food collection.

4.1.2 Plant Lighting System

Sufficient illumination intensity is provided for efficient plant growth by using fiber optic technology to directly collect and route sunlight. The light is provided in the wavelengths most usable by the plants (i.e., the visible wavelengths, with emphasis on red and blue). Sunlight is collected using Sun tracking arrays of Fresnel lenses. These lenses are specifically constructed to focus each wavelength at a specified point. The fiber optic fibers are positioned to collect only those frequencies useful to the plants. Harmful frequencies (infra-red (IR), ultraviolet (UV), etc.) are not collected for transmission. The collected light energy is transmitted through fiber optic cables formed from numerous smaller cables fused into a trunk line. This trunk line pipes the light to distribution buses from which it is directed to PGUs. Artificial light is provided during the dark-side orbit. Fluorescent lights were used in this design because of their simplicity, relatively low weight, and reliability.

Wheat, the primary study crop, can thrive under continuous light. A fluctuation between light and dark periods during each orbit, 16 times per day, may alter normal growth and development. Illumination intensity is adjusted for dark-side orbit to keep plants photosynthetically active. Light intensity is limited by available electrical power and by the resulting temperature control requirements.

4.1.3 Thermal Control

CELSS thermal control must maintain module interior temperature within a relatively narrow range (12-28°C) for efficient plant growth. Heat loads are primarily contributed

by plant lighting system. Waste regeneration system contributes a second high, concentrated thermal load for a few hours each day. Additional heat is generated by electrically powered equipment on board.

Forced air circulation and the natural transpiration of moisture from plants are used to maintain growth temperature range. Cooling air velocities are kept low to avoid inhibiting plant growth. These low cooling air velocities dictate that cooled air be used to remove maximum heat load per cubic foot of cooling air. A relatively large ECLSS cooling capability is provided because the design uses ambient air cooling.

The concentrated, high-temperature thermal load from the waste regeneration reactor is controlled with a water jacket and heat exchanger.

Heat from CELSS module is routed to the Space Station heat bus for possible use in Space Station processes. Excess heat is radiated to space by Space Station radiators.

4.1.4 Nutrient Supply

The nutrient supply system keeps plant roots moist and provides the required nutrients. Nutrient solutions are monitored and adjusted for each plant species grown. A constant aerated nutrient supply is pumped to the roots. The exhausted nutrient is removed from the root zone by aspiration.

Aspirated air, with entrained nutrient solution, is passed through a water separator. The used nutrient solution is automatically monitored for composition and pH. The nutrient solution elements are replenished, pH and solution concentration adjusted, and then the solution is recycled to roots.

Particulates and some contaminants in the nutrient solution are filtered out as the solution is recirculated. When the dissolved contaminants reach upper-limit levels, old nutrient is dumped to the waste regeneration system and fresh solution is added.

4.1.5 Atmosphere Control

The plant atmosphere is controlled for composition, pressure and contaminant concentration. Carbon dioxide concentration is a variable for different plant growth conditions. Carbon dioxide levels can be maintained at desired concentrations by regulating output from waste regeneration and from the Space Station atmosphere. This may require reserve carbon dioxide tanks to capture SCWO exhaust carbon dioxide. Oxygen levels build up as the plants produce oxygen and will be controlled by oxygen scrubbers. Contaminants are removed by filters and/or catalytic burners.

4.1.6 Waste Regeneration

CELSS operation produces a high volume of organic waste material. An SCWO unit is used to process the plant waste. Other organic Space Station waste material is processed with the plant waste. Oxidation products are reclaimed for reuse in the nutrient supply, for replenishing carbon dioxide and nitrogen in the atmosphere, and for potable water supply.

Waste material is ground into very fine particles then mixed with water to form a slurry. The slurry is preheated and sent to the SCWO reactor. Preheated air and oxygen are injected, which results in waste oxidation. Supercritical steam from this oxidization is vented to the preheat exchangers and subsequently separated from the entrained carbon dioxide and nitrogen gasses. The steam is condensed into potable water. Carbon dioxide and nitrogen, the other major gaseous outputs, are compressed and stored for later use. Nongaseous oxidation products are passed through a salt separator. This unit salvages plant nutrients by using pressure and temperature variations to selectively precipitate desirable compounds. Unusable wastes are sent to storage pending disposal.

4.1.7 Food Processing

Food processing includes harvesting mature plants and separating food from inedible biomass. Mature plant trays are removed from the growth unit, inserted in the harvest machine, which clips off stems while an air flow pulls and the robot arm pushes the stems, crop, and roots into the harvester chamber. A cross flow of air causes less dense particles to deflect while denser crop material continues relatively straight through the

chamber. Separate collection containers are used to hold the crop and inedible biomass. Collected wastes are ground to fine particles and stored until the next waste regeneration cycle. Edible crop material is stored until storage containers are full. The Space Station crew is alerted to retrieve the food, a crew member enters the CELSS module and empties the food container.

4.1.8 Robotics

CELSS module operations are fully automated. This automation includes robots unit that perform all planting, harvesting, waste handling, and some maintenance operations. Space Station crew members normally only enter the module to perform unusual maintenance, conduct repairs, or remove food supplies.

One robot handles the planting operations. Its primary functions are to remove trays of mature plants from the growth unit, insert newly seeded trays to maintain crop growth sequence, and move mature plant trays to the harvest equipment.

The second robot processes plant trays through the harvest equipment. It also handles the trays through the reseeding operation and replaces empty seed mat cartridges in the seeder.

4.1.9 Module Structure

With the exception of minor changes, the common module shell is used as the primary structure; the secondary module structure is CELSS unique. Working area height is increased to more efficiently use interior volume for plant growth. Secondary support structure is added for each CELSS systems equipment.

4.2 SYSTEM DESCRIPTION

Each CELSS system (defined above) is described in the following sections.

4.2.1 Plant Growth Unit

The PGU design was selected to meet the requirements defined in section 8. This design comprises a series of plant trays arranged in a tier eight high. Sufficient plant growth area (for two crew members) is attained by stacking four tiers to a module cross section and using six cross sections to obtain 40-m^2 growth area (fig. 4.2-1).

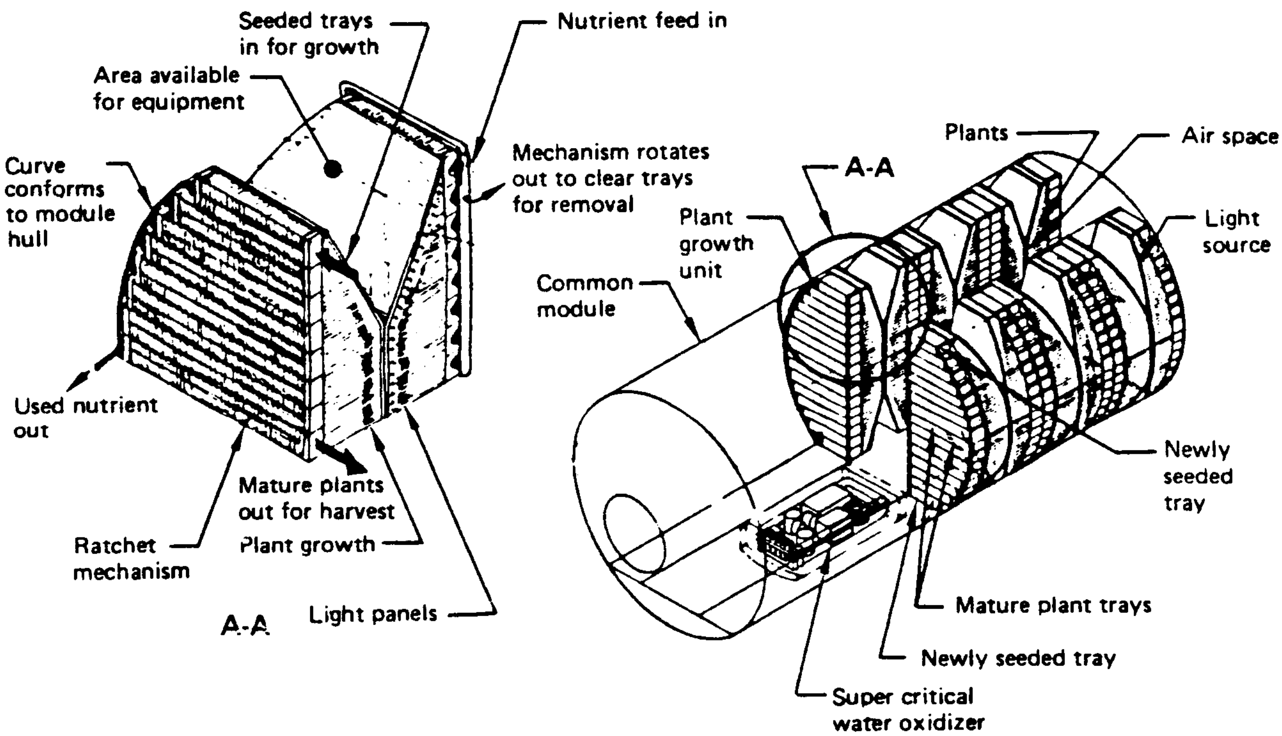


Figure 4.2-1. Plant Growth Unit Configuration

Each tier is supplied with nutrient, (sec. 4.2.4) and light, (sec. 4.2.2). When the plants are mature, the trays are removed individually and transported to the harvest equipment. A fresh tray with a seed mat is inserted in the empty tier and all remaining trays are moved one space nearer the center mature-tray position (fig. 4.2-1, sec. A-A).

4.2.1.1 Growth Unit Arrangement

The PGUs are configured to take advantage of plant growth patterns and keep light sources (luminaries) close to growing plants. The units are divided into eight increments to permit a close match with plant height change and harvest cycle (fig. 4.2-2). The PGUs are arranged (fig. 4.2-1) to maximize growing area per volume in a cylindrical module cross section. Access to all growth units is ensured by a central aisle running the module length.

Twenty-four growth units (tiers) with eight trays each provide adequate plant growth area to satisfy caloric requirements for two adults. A 20% reserve is included in this calculation (table 6.5-1, 100% wheat).

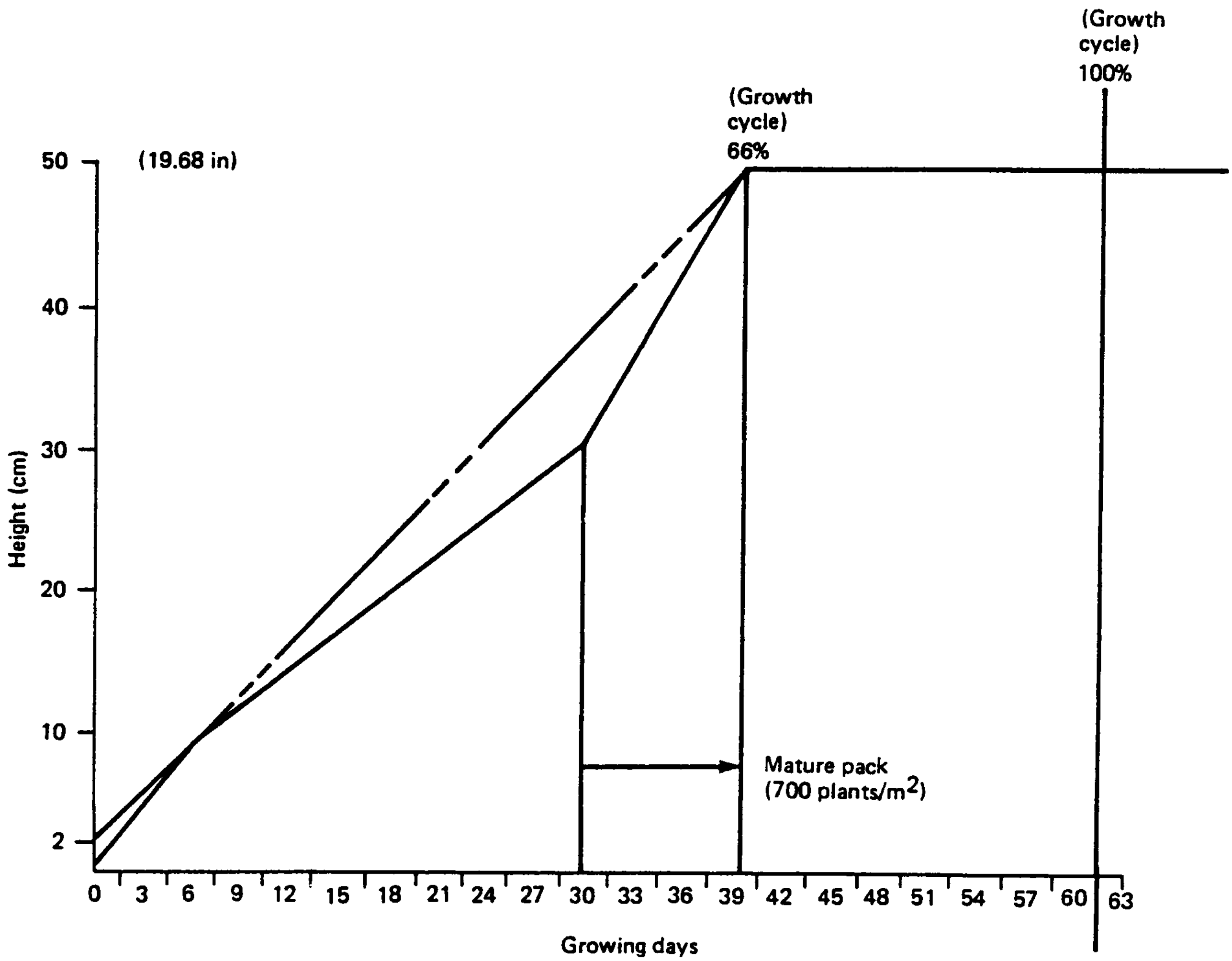


Figure 4.2-2. Plant Growth Pattern (Wheat)

4.2.1.2 Plant Trays

The plant trays have an 8-in^2 cross section. An 8-in width is an efficient size to make eight increments in each growth unit. An 8-in depth should provide ample space for plant roots and nutrient distribution. The tray length is determined by module cross-section contours. Stacking the trays in tiers of eight in each quadrant of a module cross section generates tray lengths increasing from 25 to 56 in as plants grow. The accordion trays are compressed to 25 in immediately after seeding. As seeds germinate and grow, the trays are moved toward module center. The plant lighting panels are arranged to accommodate increasing plant height at each succeeding tray position. At the same

time, trays expand to conform to module contours and provide more room for root and stem growth. The accordion tray construction permits planting seeds at a very high density. Therefore, mature plants, at maximum tray expansion, can have a density of 700+ plants per square meter growth area, (fig. 4.2-3).

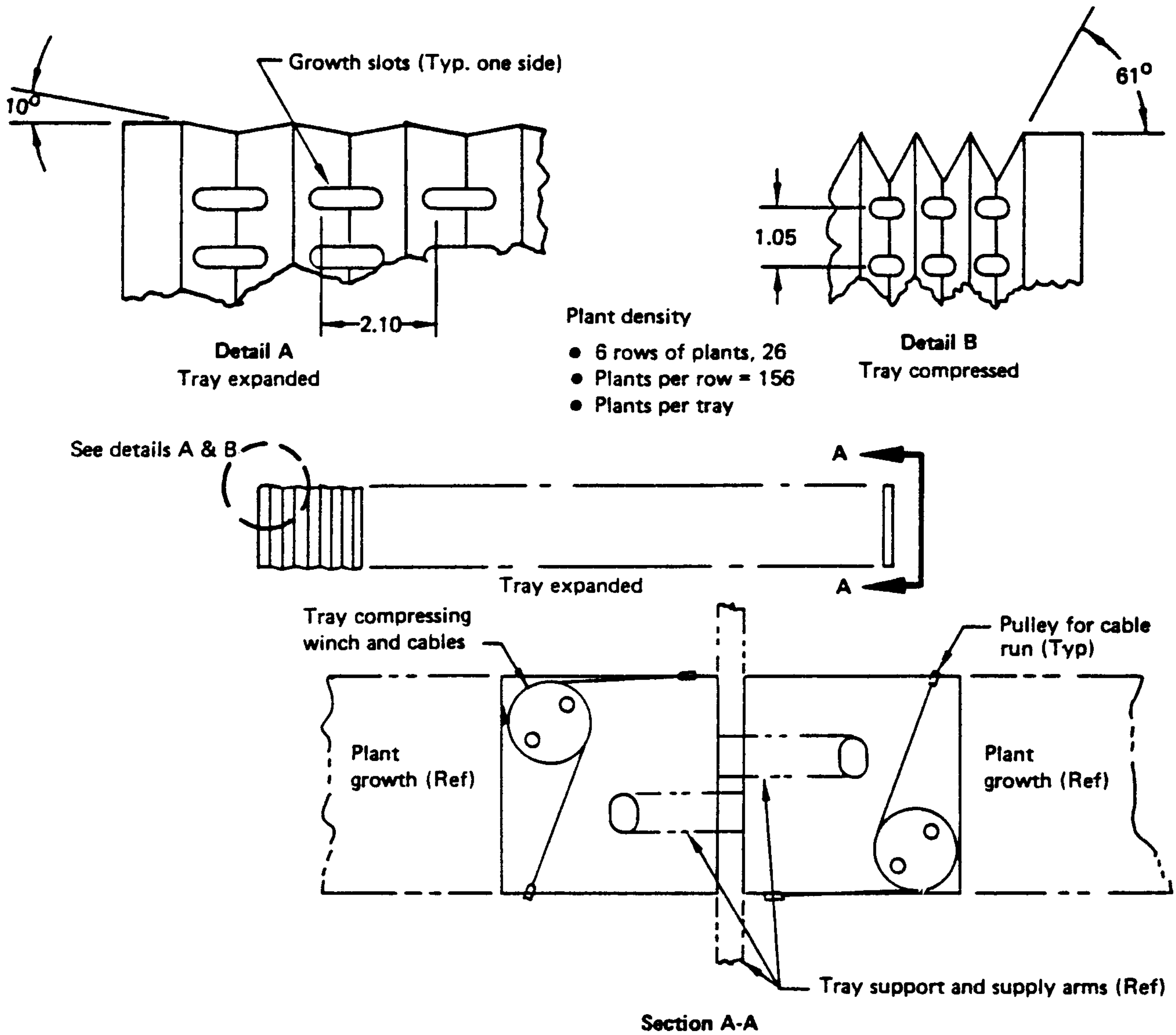


Figure 4.2-3. CELSS Tray Concept

4.2.1.3 Seeder

The equipment to reseed trays after harvest is not a direct growth unit item, but is essential to successful growth unit operation. Seeds are shipped from Earth embedded in a foam tape (seed tape) that is coated with an adhesive on one side. The preloaded seed

tape cartridges are placed in the seeder device. As the tray is inserted into the seeder, a power drive feeds the tape out over the tray. The unseeded tray has the tape applied to one surface. Seed locations are matched to slots in the tray surface, (fig. 4.2-4). A ribbed roller then presses the tape into place. After the tray is covered with tape, a solenoid-operated knife cuts the tape. If no other trays require seeding, the robot removes and stores the tape cartridge (fig. 4.2-5).

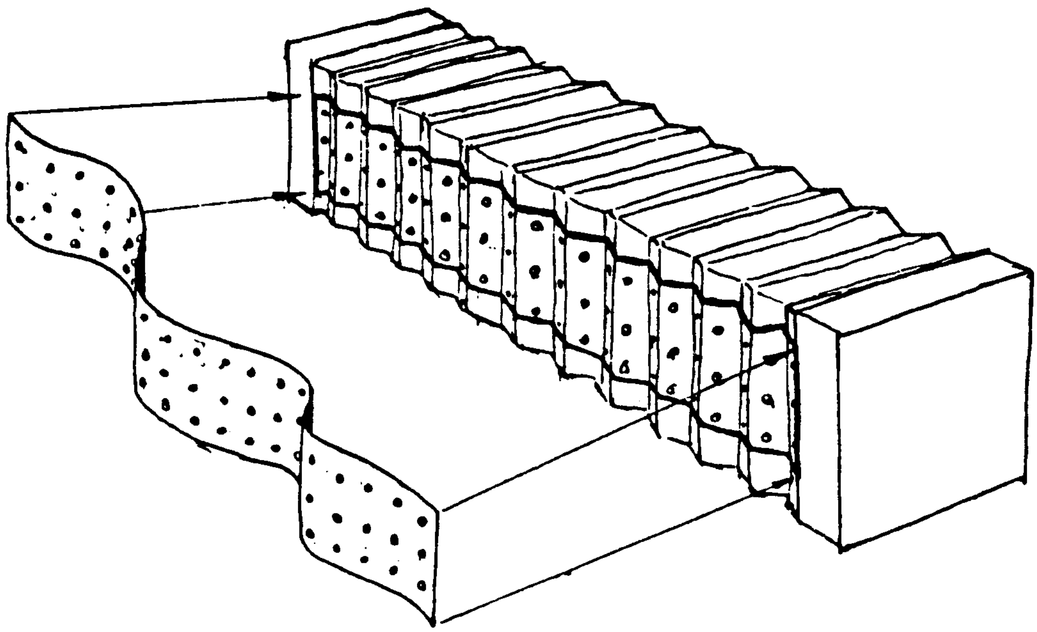


Figure 4.2-4. Tape Application to Tray

The seed tape must be kept cool and dry until a seed tray is placed in the seeder unit. Preseeded tape is kept in closed cartridges for safe storage and easy handling. Cartridges hold sufficient tape to seed 18 trays. Eighteen cartridges hold enough tape for 90 days for two adults.

Power feed for the tape consists of an electrically driven roller that removes the tape from the cartridge. The roller accesses the tape through a slot in the forward cartridge feed lip. Seed registration with tray slots is maintained by locating sprockets and perforation in tape border.

Tape-to-tray adhesion is accomplished by a ribbed roller that presses tape onto the tray and down into the accordion depressions. A pneumatic piston operates the roller and regulates pressure. Roller registration on the tray is maintained by alignment of roller ribs in tray accordion depressions. Tape is cut to length by a solenoid-operated knife acting against a metal platen attached to the tape cartridge.

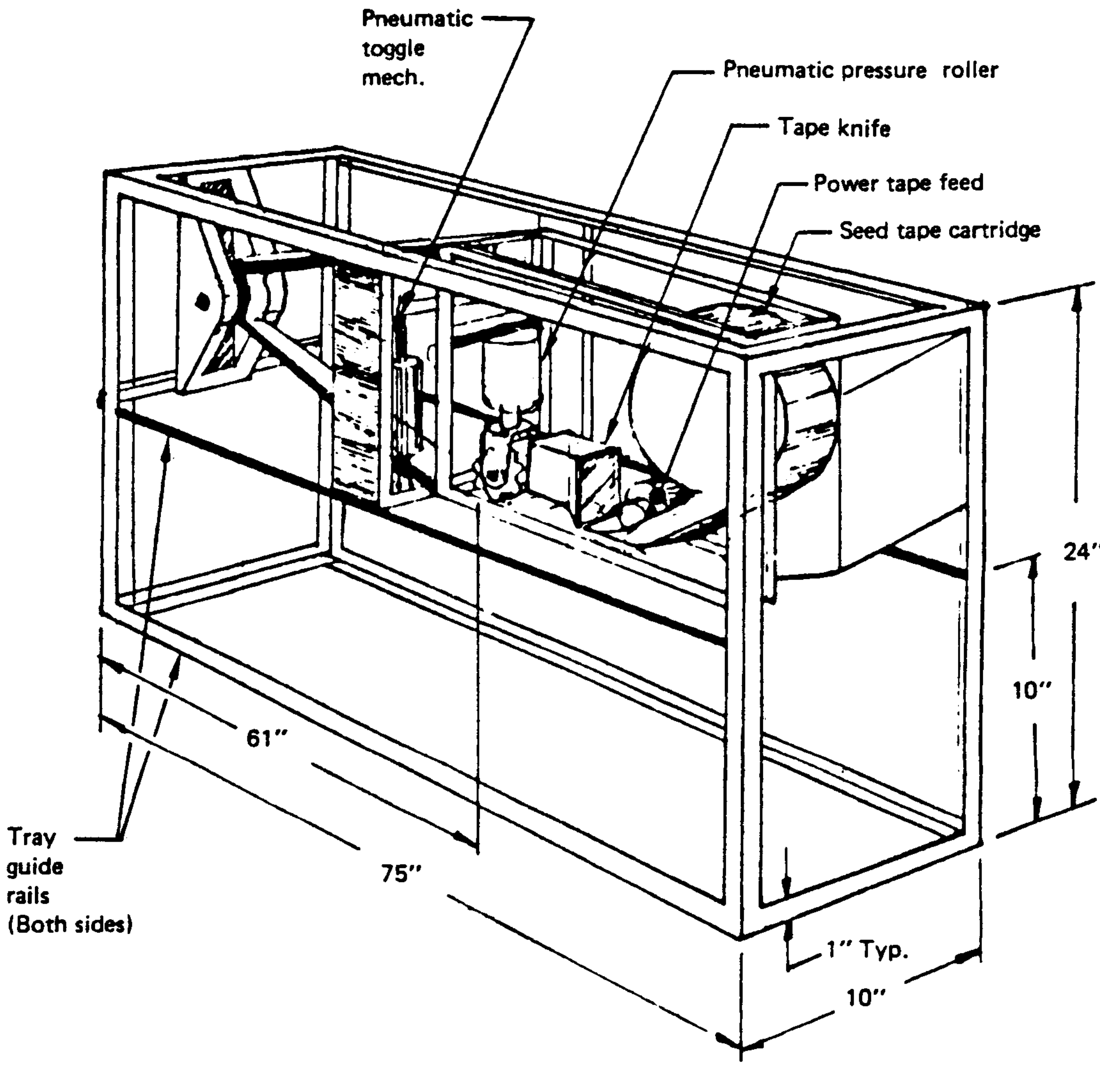


Figure 4.2-5. CELSS Seeder

After a tray is seeded it is removed from the seeder. The taping mechanism is pivoted out of the way to facilitate tray removal. A pneumatic piston provides the rotating force.

4.2.1.4 Parts Listing

Tables 4.2-1 through 4.2-2 list major plant growth tray and seeder unit components.

4.2.2 Lighting System

The plant lighting system selection considered four options. The first was a solar collector (only) based system. The second was a totally artificial-based system. The

Table 4.2-1. CELSS Plant Growth Tray Assembly

Equipment	Quantity required	Size	Product in	Product out	Utility and power requirements	Comments
Accordian tray box	216 + spares	8" x 8" x 56" (expanded)	Nutrient solution and air	→	Support structure nutrient supply system	Needs method for compression, attach points for support and transport, nutrient supply port
Seed mats	192 x cycles	8" x 54"	Seeds	Crop	Support (tray) nutrient supply system	
Telescoping spray tube	216 + spares	1" x 54" (extended)	Nutrient solution and air	→		
Tray end (nutrient input)	216 + spares	8" x 8"			Attachment to accordian tray	Contains nutrient and air inlet port (into telescoping tube)
Tray end (blind)	216 + spares	8" x 8"			Attachment to accordian tray	Attaches to blind end of telescoping tube

Table 4.2-2. Seeder

Equipment	Quantity required	Size	Function	Utility and power requirements	Comments
Tape cartridge	20/90 days	12" dia x 6"	Hold and dispense seed tape	None	Robot changes out cartridges as required
Tape feeder	1	4" dia x 6"	Feed tape out to roller	28 VDC, 100W	
Tape knife	1	6" x 4" x 6"	Cut tape to length	28 VDC, 200W	Intermittent pulse operation-solenoid powered shear
Pressure roller	1	6" x 6" x 10"	Presses tape onto growth tray	Pneumatic-station air at 100 psi electrical valve regulator	Pneumatic actuator with "rubber" roller
Subframe toggler	1	4" dia x 10"	Moves seeding system into and away from growth tray	Pneumatic-station air at 100 psi electrical valve regulator	Pneumatic actuator
Subframe	1	75" x 7" x 11"	Carries seeding equipment, rotates in joint	—	1" x 1" angle, some non-metallic material such as kevlar composite
Frame	1	75" x 10" x 24"	Registers tray place, provides pivot plus reaction base for seeder	—	1" x 1" angle, some non-metallic material such as kevlar composite

third and fourth were two variations on hybrid systems using solar illumination on light-side orbit and artificial lighting using one-tenth illumination level on dark-side orbit to conserve power.

A hybrid system using solar collectors and fluorescent lamps is identified as best compromise illumination system during preliminary design tradeoff analysis. This solar plus fluorescent system uses reduced plant illumination intensity during dark-side operations to reduce power consumption. A discussion of each system follows.

4.2.2.1 All-Solar Lighting

The collected sunlight is conducted through fiber optic cables to be distributed from luminaries over the tiers of plant trays. A Fresnel lens system is used as the solar light concentrator. The system-unique characteristics permit selective light frequency collection (filter IR and UV) by selective positioning of the fiber optic cables. Fiber optic light cables from each lens are bundled together into trunk lines then run through the module hull. These bundles are then broken out into individual cables. Cables are routed to PGUs where they are connected to terminal illuminators. Varying cable count to each illuminator varies the light intensity. Internal illuminator controls permit reducing light intensity without moving cables.

Tradeoff analyses determined that a solar collector lighting system saves significant electrical power. Because solar light provides the plant illumination, the station need only expend the power to keep the collector Sun oriented, an estimated 373W. Working against the solar-only collector system are two factors. First, solar lighting will be on for approximately 60 min and off for approximately 30 min each orbit. Frequent, short day- and night-cycle exposure may have an adverse effect on plant growth. Second, is the anticipated reduced yield when compared to continuous full lighting. This causes a volume penalty by requiring additional PGUs. These effects, added to the unknown effects of microgravity on plants, result in caution in selecting solar collector-only lighting as the CELSS lighting system.

4.2.2.2 All-Artificial Lighting

Providing effective plant growth illumination levels and frequencies with artificial lighting is possible using available electric lamps. Fluorescent tubes, xenon lights, and high intensity discharge (high-pressure sodium) lamps were compared. The power required for the desired illumination levels for a two-member module are-

Fluorescent	79.2	kW
Xenon	306.0	kW
HID (high-pressure sodium)	77.4	kW

These values probably represent an unrealistic allocation from the 1999 proposed Space Station power budget (~210 kW). This consideration resulted in dropping artificial-only lighting as primary illumination system when compared with other available systems (fig. 4.2-1).

4.2.2.3 Hybrid Lighting

Combining solar lighting during light-side orbit with artificial lighting during dark-side orbit provides continuous light and reduces power demand. This hybrid system provides any length of day required by plants up to a continuous 24 hr of illumination. Reduced illumination intensities during dark-side operations are necessary to conserve power. Artificial lights equivalent to solar-light levels (750 μmol/m^2/s) requires over 75 kW. Reducing artificial illumination to 750 foot-candles (75 μmole/m^2/s) may keep plants in a photosynthetic state while reducing power consumption as follows:

Fluorescent
Xenon
HID (high-pressure sodium)

Comparing these lamp sources requires considering additional lamp characteristics. For example, warm-up time for lamps requires energy expenditure without appreciable light generation. Short warm-up times are preferred in lamp design. Xenon and HID lamps require relatively long (several minutes) warm-up time and generate intense, localized heat loads. Fluorescent tubes require no appreciable warm-up time, do not generate intense, localized heat. Ballast losses are comparable for each lamp at a nominal 10%.

HID lamps are three to four times more efficient than fluorescent in terms of lumens produced per watt. HID intense heat generation makes them unsuitable for direct plant illumination at the required very close plant-to-lamp spacing. An alternative approach using fiber optic light pipes solves the heat problem; however, the efficiency losses encountered in focusing and transmitting HID light reduce overall efficiency by 30% to 60%. Compared to fluorescent lights in fixtures directly over the plants, the power

requirements are nearly identical for each lumen at plant canopy. Volume, cost, and mass values also favor a solar-plus-fluorescent system.

A hybrid plant lighting system using solar light when available and supplementing with fluorescent light during dark-side orbit is selected as the study baseline plant growth lighting system (fig. 4.2-6).

4.2.2.4 Solar Light Collection

Solar light is collected by a number of Fresnel lenses focusing solar rays onto the ends of glass fibers (fig. 4.2-7). Solar collector lens area totals about 62.9 m^2 to provide 1000 $\mu mol/m^2/s$ to 40 m^2 of plant growth area in the module. A tracking mechanism maintains exact alignment of the solar ray collector with the Sun. This pointing system moves very slowly as the Space Station precesses during its orbit. Slow speed combined with microgravity allows a small motor to power the pointing system. Net system power consumption is about 373W.

A 2-mm glass fiber exits from each lens then is combined into bundles and routed to PGUs. Study design assumed a continuous cable from lens to illuminator. In practice, breaks in each cable are necessary for handling, maintenance, and system upgrading. These breaks can cause from 2% to 35% light loss depending on technique used. Rotating joints are avoided in study design by using slack cable loops. This approach avoided the 20% to 30% losses common to fiber optic rotating joints. No joints are used at hull penetration to avoid light loss. Current hull penetration technology is adequate to safely permit penetration by unbroken bundles.

4.2.2.5 Fiber Optic Cables

The fiber optic light transmitting cables are made up of bundles of individual glass fibers. Each cable is 2 mm in diameter and collects and transmits light from one Fresnel collector lens. Current fiber optic technology uses germanium-doped fibers to enhance transmission quality. This technology is based on high-frequency light (UV) used for fiber optic communication systems. Several glass types are used in fiber construction. Most glass types are tuned to a frequency range. Glass additives are used to filter undesirable frequencies. These characteristics will aid in removing UV and IR light in transmission to plants. Improved and frequency-tuned doping compounds and glasses will reduce light loss at bends and junctions.

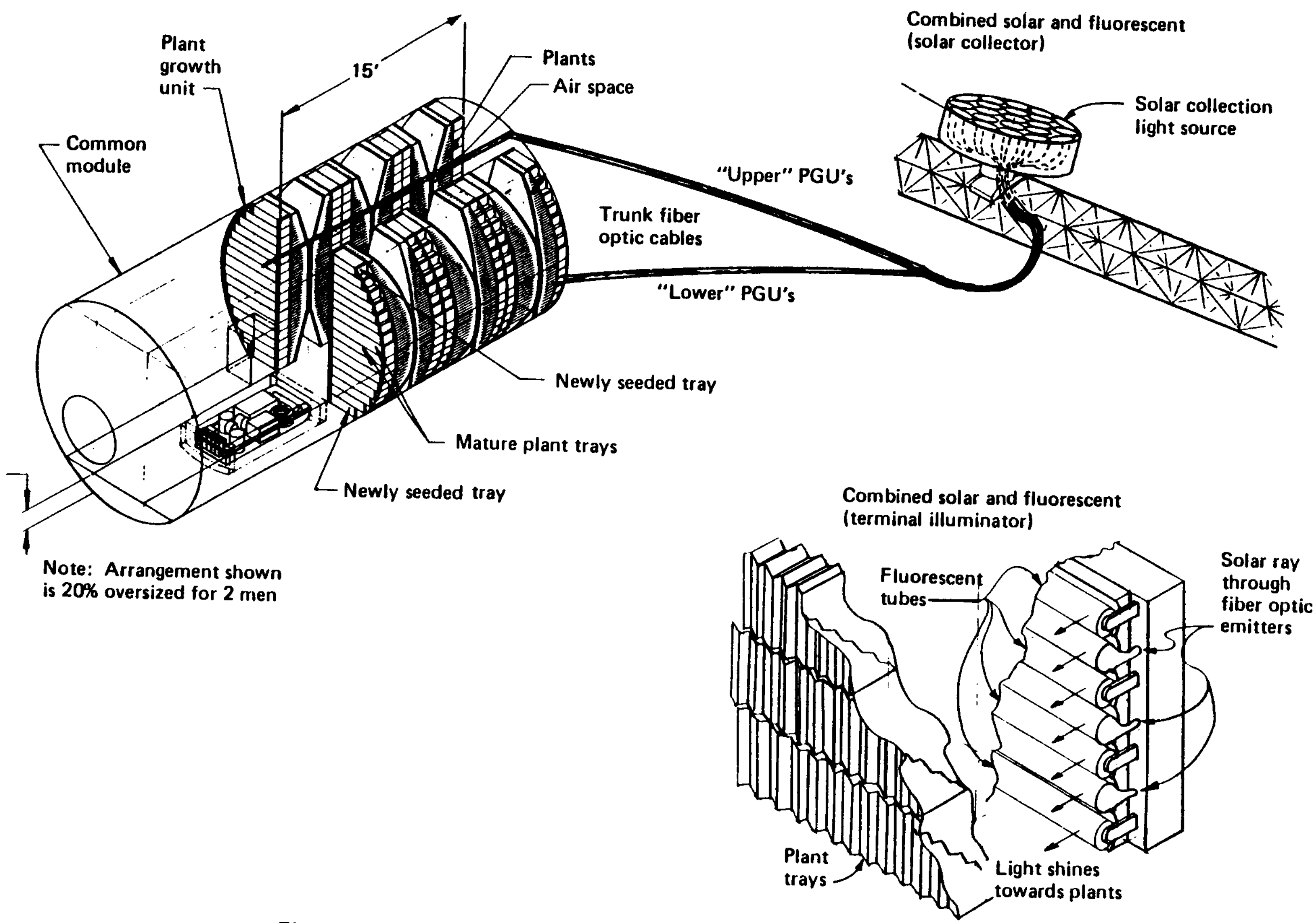


Figure 4.2-6. Solar and Fluorescent Baseline Plant Lighting System

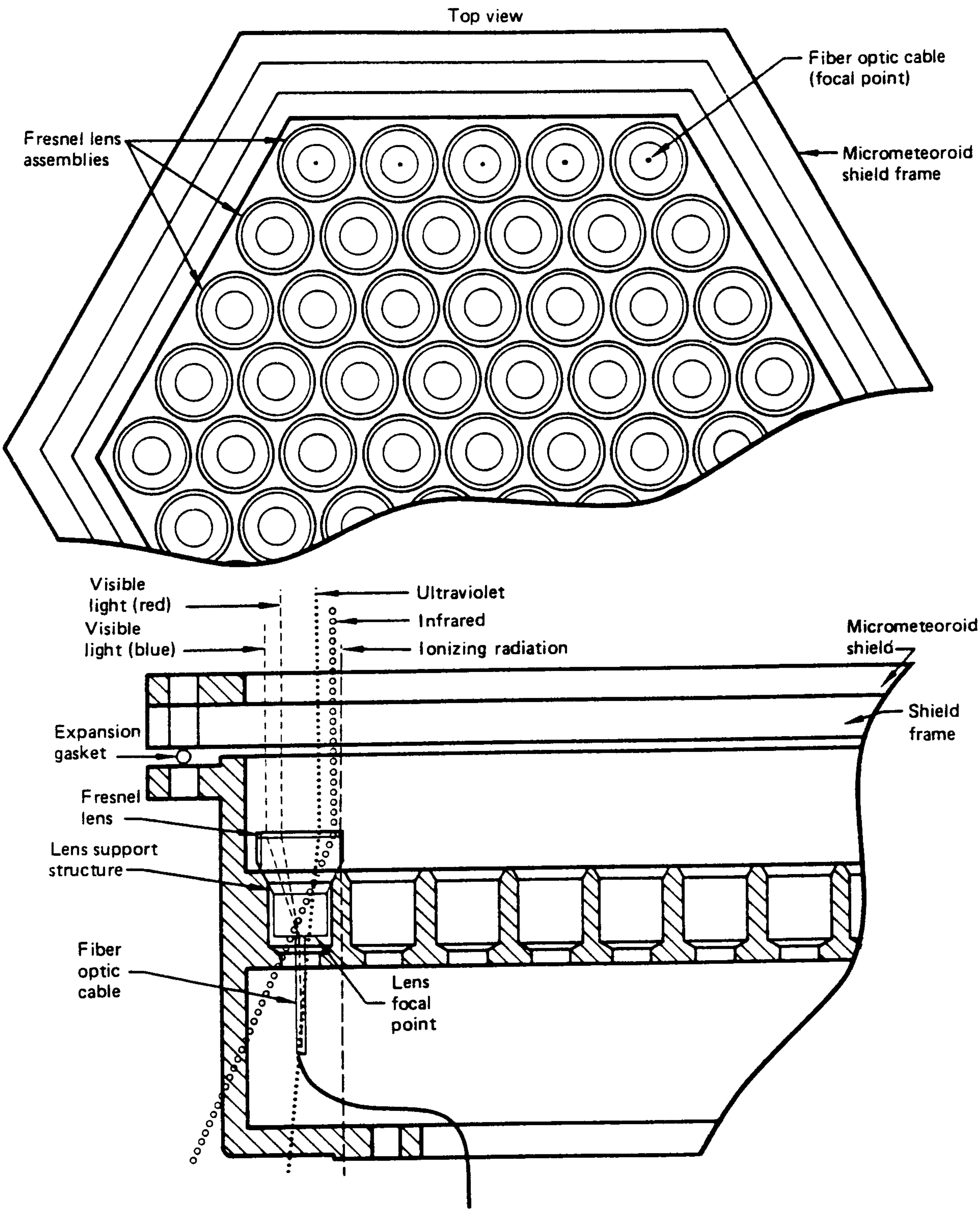


Figure 4.2-7. Fiber Optic Solar Ray Collector (Side View)

4.2.2.6 Solar Light Distribution

Solar light distribution uses an inverted-tree structure to direct desired light intensity to each PGU. Light is transmitted from fiber optic cables to primary beam splitters at each tray location. An aperture control mechanism or adjustable shutter is located between cable end and beam splitter. Primary beam splitters transmit light to eight secondary beam splitters forming luminaries to emit light to each tray. Each luminary beam splitter (fig. 4.2-8) has a series of steps on the surface away from the plants. These step surfaces are silvered to reflect light onto the plants. Reflecting steps are staggered to ensure an even distribution of light . A reflector over each luminary helps reduce light loss and also serves as a reflector for the artificial lighting system.

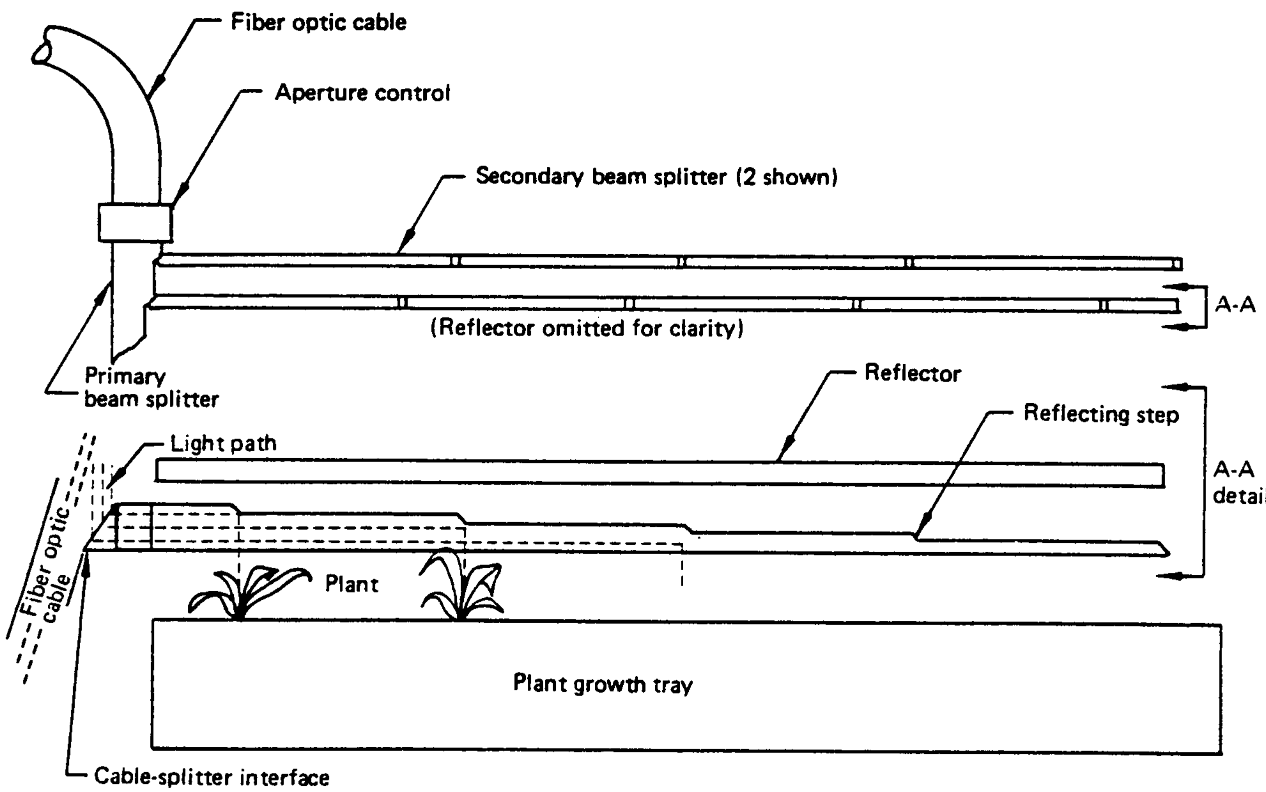


Figure 4.2-8. Fiber Optic Luminaire

4.2.2.7 Artificial Lights

Light from fluorescent lamps is provided, when necessary, during dark-side operations. Illumination intensity equivalent to collected solar light is precluded by high electrical power requirements (75 kW) for artificial light. A light intensity

of 750 $\mu mol/m^2/s$, is used to maintain plants in a photosynthetic state. Providing this intensity with fluorescent tubes requires about 11-1/2 kW, including ballast losses.

The fluorescent tubes are installed in the same luminaries with fiber optic beam splitters (fig. 4.2-9). One reflector serves both types of light emitters. Heat loads generated at the light-emitting surface are comparable for both types. Approximately $12W/ft^2$ of tray area (41 Btu) from the beam splitters and $17W/ft^2$ of tray area (58 Btu) from fluorescent tubes. Common cooling provisions will handle luminary heat loads for all lighting conditions.

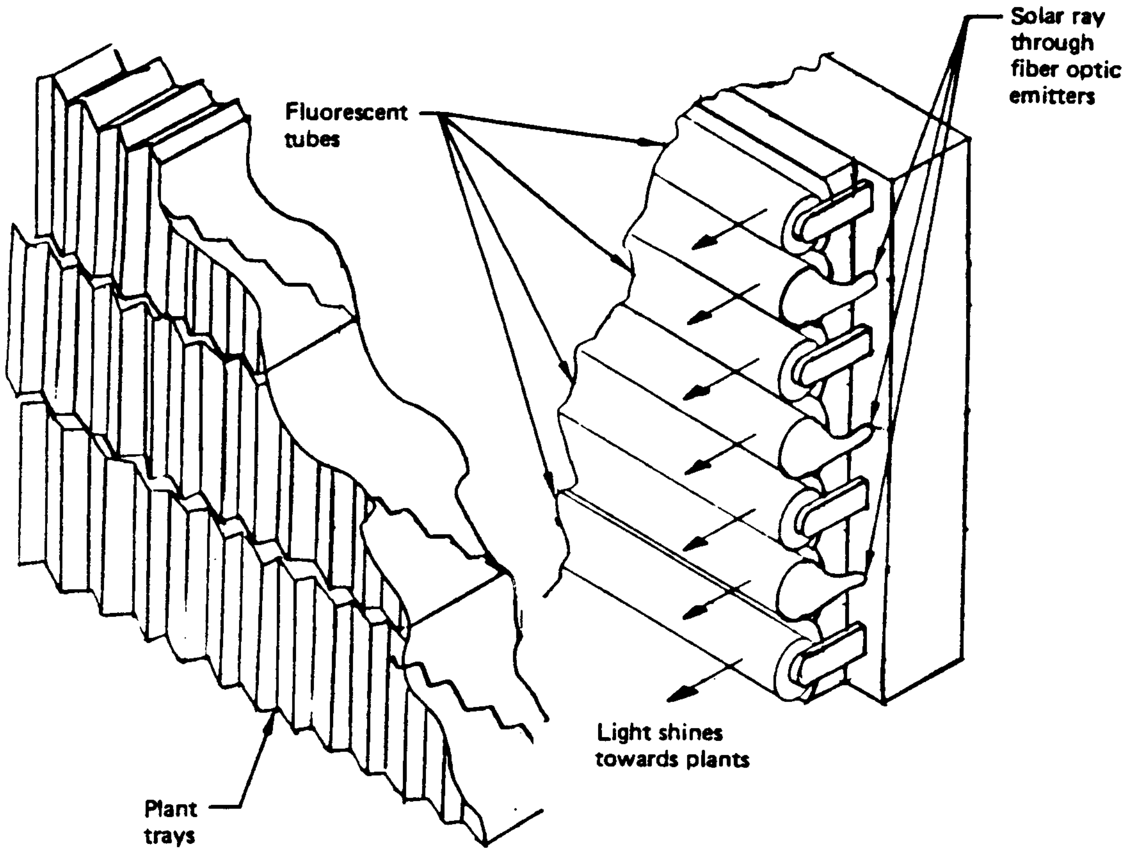


Figure 4.2-9. Combined Solar and Fluorescent

The fluorescent lamp frequency spectrum is adequate for plant growth. Modifications in phosphor coatings can increase red frequency output, which may enhance plant growth. The fluorescent lamp mercury content is a major health hazard. Specially design sealed lamps and/or fixtures may be required to prevent mercury escape.

4.2.2.8 Lighting Efficiency

Lighting efficiency can be defined in terms of lumens per square foot of plant area per watt of electrical power.

<u>Efficiency: lumens on plants/W</u>

Fluorescent tubes	41.3
Collected solar rays	9700

Solar light collection efficiency can also be defined in terms of light transmission per distribution efficiency.

<u>Efficiency: lumens on plant/ lumens collected</u>

Collected solar rays	0.456

The solar collectors pick up 8.0 million lumens. Fiber optic cables transmit 60% or 4.8 million lumens to the luminaries. The luminaries emit about 76% or 3.64 million lumens to the plants, or 7500 lumens per square foot. The values for lumens collected and transmitted are based on a continuous cable between the solar collectors and the luminary connections. Lights transmitted through fiber optic cables can be reduced 2% to 3% through an optimum connection and up to 20% to 30% for current technology rotating joint connections.

4.2.2.9 Parts Listing

Table 4.2-3 lists major components for solar ray lighting and fluorescent tube supplementary lighting.

4.2.3 Thermal Control

Heat is added to the CELSS module by solar lighting and by artificial lighting. Additional heat is added by the SCWO waste regeneration unit, (sec. 4.2.6.) For each watt of electrical power used, approximately 3.4 Btu of heat are generated.

Cool air circulation is the principal method selected for removing heat from the PGUs. Air is passed through heat exchangers, excess moisture is removed, and the air is recirculated. Air exchange rate peaks at about once every 2 min for maximum heat load.

Table 4.2-3. CELSS Growth Unit Lighting—Conducted Sunlight

Equipment	Quantity required	Size	Product in	Product out	Utility and power requirements	Comments
Solar collector	1	See lens	Light Heat →			Composed of 2712 lenses
Solar collector lens	2712	6.77" dia ($35.997\ in^2$)	Light Heat →			113/PGU = 2712 lenses ($677.94\ ft^2$ lens)
Fibers (quartz)	2712	2mm dia x 100 ft	Light →			
Fiber optic cable	24	26mm x 100 ft (.52 lb/ft)	Light →			Composed of 113 fibers each = 2712 fibers 1 cable/ tier
Beam splitter (one at each tray)	192	10" long x 2" x 2" (stepped down – use .6 factor)	Light →		Support	Glass transmits light from tray cable to tray beam splitters
Beam splitter (luminaire)	1152	Tray length X 2" x .25" (stepped down – use .6 factor)	Light →		Support and cooling	Glass 4/tray (6/tray) as required for even light distribution to plant canopy
Light sensors	192		Light	Sensor signal	Support	To measure light level, detect light failure or malfunction
Reflectors	192	Tray length x 8" x .375	Light →		Support	Reflect back and conserve light lost from tray beam splitters
Light aperture control	192	2" x 2" x 3" (estimate)	Control signal	Shutter motion		Shutter up stream surface (toward light source) is a mirror
Servo motor or solenoids	192		Electrical power	Motion (to shutter)		Operates aperture control shutter
Micro-processor "controller"	1		Sensor signals	Control signals		Varies light intensity by controlling aperture shutter
Tracking mechanism	1		Sensor signals	Control motion	115 VAC or 28 VDC 373 W	Keeps collector lenses directed at sun
Florescent lamps	192	Length to match tray length	Electric power	Light and heat	Mounting, cooling, 21.74 watts per sq ft (stand by)	(1) or 2 lamps per tray probably special lamps

Table 4.2-3. CELSS Growth Unit Lighting – Conducted Sunlight (Continued)

Equipment	Quantity required	Size	Product in	Product out	Utility and power requirements	Comments
Ballasts	192		Electric power	Electric power plus heat	Electric power = to 10% of lamp power	1/lamp (1) or 2 lamps per tray
Reflectors	192	8" x tray length x .375	Light ⟶		Structural supports	Use same reflector used with solar light
Light Sensors	192		Light	Sensor signal	Support	
Light intensity control	192		Control signal	Light intensity adjustment		
Micro-processor "controller"	1		Sensor signals	Control signals		Varies light intensity

Heat exchangers are cooled by a water circulation system, heat is sent to a Space Station thermal bus, and unneeded heat is radiated to space.

4.2.3.1 Plant Growth Unit Cooling

Heat from light-emitting surfaces and from impinging light energy combine to form the major thermal load. Full illumination with collected solar rays creates approximately 82,000 Btu/h. Maintaining plant temperatures between 70°F and 90°F (20°C and 30°C) requires approximately 2000 ft^3/min of air circulation. Air flow is directed past and through plant growth trays to carry heat toward adjacent luminaries. The air circulated past and through luminaries is allowed to gain more heat than air around adjacent plants. Air passing over light-emitting surfaces is allowed to reach temperatures as high as 120°F. Cooling effects of water transpired from the plants helps minimize air circulation requirements. Energy required for air circulation system adds heat that must be removed.

4.2.3.2 Waste Regeneration Cooling

When operating, the waste regeneration system operates at 84°F to 1240°F (450°C to 670°C). This concentrated heat load is generated by the SCWO reactor, a small, high-

pressure device. Some of this heat is used to preheat entering waste material. The remaining heat is removed by circulating water through a jacket and then through a heat exchanger. Heat that is not used in other processes is radiated to space.

4.2.3.3 Cooling Air Circulation

All air circulation must be forced-air generated because convection currents do not occur in microgravity. Air to cool PGUs is forced, by a fan, through four main ducts along the PGUs (fig. 4.2-10). These ducts feed distribution passages that direct air past plant trays and luminaries. Warm air is drawn through heat exchangers as the fan forces air into the distribution ducts. Chilled water circulating through the heat exchangers removes and carries heat to Space Station thermal buses. Excess heat is then radiated to space.

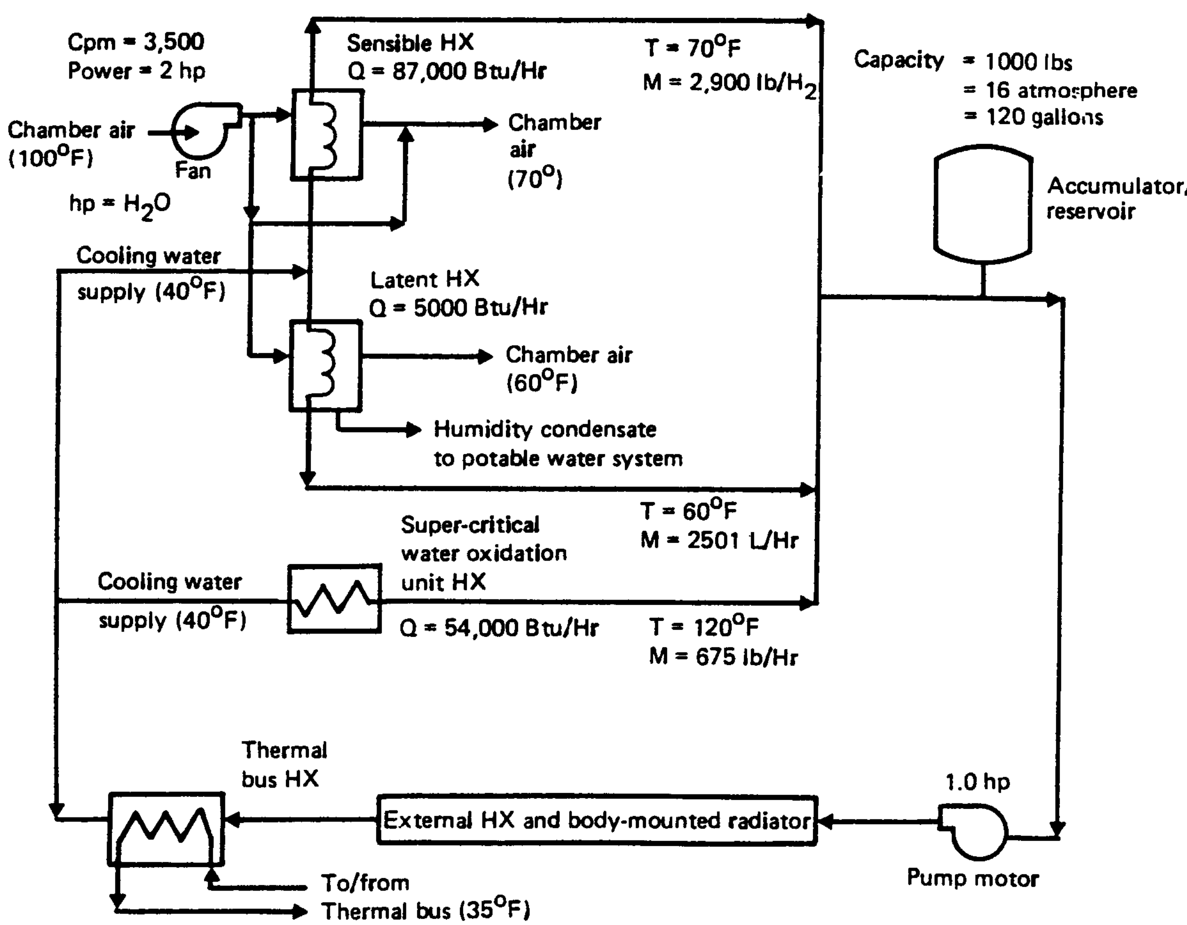


Figure 4.2-10 Cooling Air Flow Diagram

4.2.3.4 Parts Listing

Tables 4.2-4 lists major CELSS thermal control system components.

Table 4.2-4. CELSS Thermal—Cooling

Equipment	Quantity required	Size	Product in	Product out	Utility and power requirements	Comments
Sensible heat exchanger	1		Warm air / Cool H_2O	Cool air / Warm H_2O	Air flow and cooling water	Cooling capacity required: 87,000 Btu/hr
Sensible heat exchanger fan and motor	1	1.7 ft^3	Air ⟶		Either 28 VDC 115 VAC 1600 W	16" dia fan to move 3500 CFM
Latent heat exchanger	1		Warm moist air / cool H_2O	Cool dry air water / warm H_2O	Circulating air and water	Removes up to 5000 Btu/mv from moist air
SCWO heat exchanger	1	6" dia x 22" 524 in^3	Cold H_2O (40° F)	Hot H_2O (120°F)		* Volume = net 622 in^3 – 98 in^3 675 lb H_2O/hr
Accumulator	1	16 ft^3	Water ⟶			Capacity 120 gallons (1000 lb)
Pump and motor	1	1.2 ft^3	Water ⟶		Either 28 VDC 115 VAC 800 W	Pumps cooling water
Thermal bus exchanger	1	Same as priced for common module in phase B proposal				
External heat exchanger and body mounted radiator	1	Same as priced for common module in phase B proposal				

4.2.4 Nutrient Supply

The CELSS nutrient supply system provides roots a constant nutrient solution bath. Two major subsystems compose nutrient supply system. The first is a nutrient reservoir where the nutrient salts are combined to create fresh base solution (i.e., Hoagland's). This system is centralized, feeding all PGU nutrient regeneration subsystems. The second is a series of PGU nutrient regeneration subsystems, one for each four PGUs. These regeneration units constantly adjust nutrient solution to maintain optimum solutions for plants.

Aeroponic systems are used to supply nutrient solution to roots (fig. 4.2-11). A spray of nutrient solution is injected into each plant growth tray through orifices in an extendable spray tube that runs the length of each tray. Aspiration removes exhausted nutrient solution from root zone.

The aspirated nutrient solution is separated from the air, analyzed for correct composition, renewed with necessary nutrient salts, and returned to the PGU supply tank.

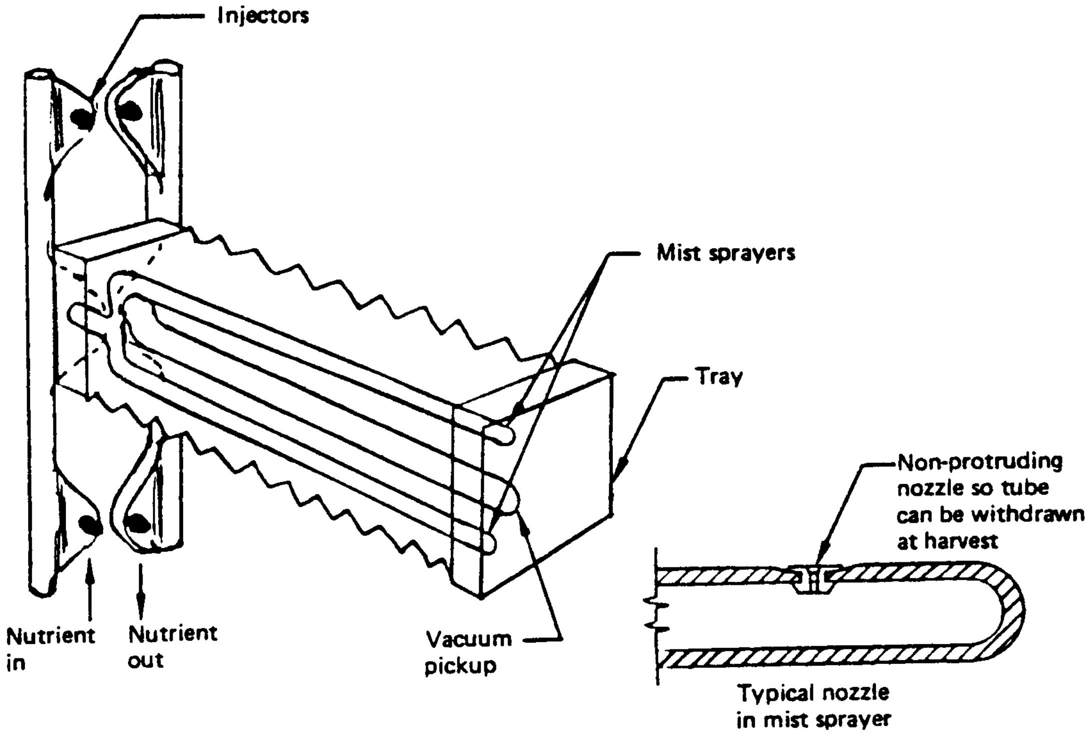


Figure 4.2-11. Nutrient Mist Sprayers

Quantity is measured and replenishment solution or water added as required (fig. 4.2-12). Particulate contamination is filtered out as nutrient solution is returned to PGU supply tanks. When dissolved contamination reaches limit levels, solution is dumped to the waste regeneration system and fresh solution is added from the main nutrient supply reservoir.

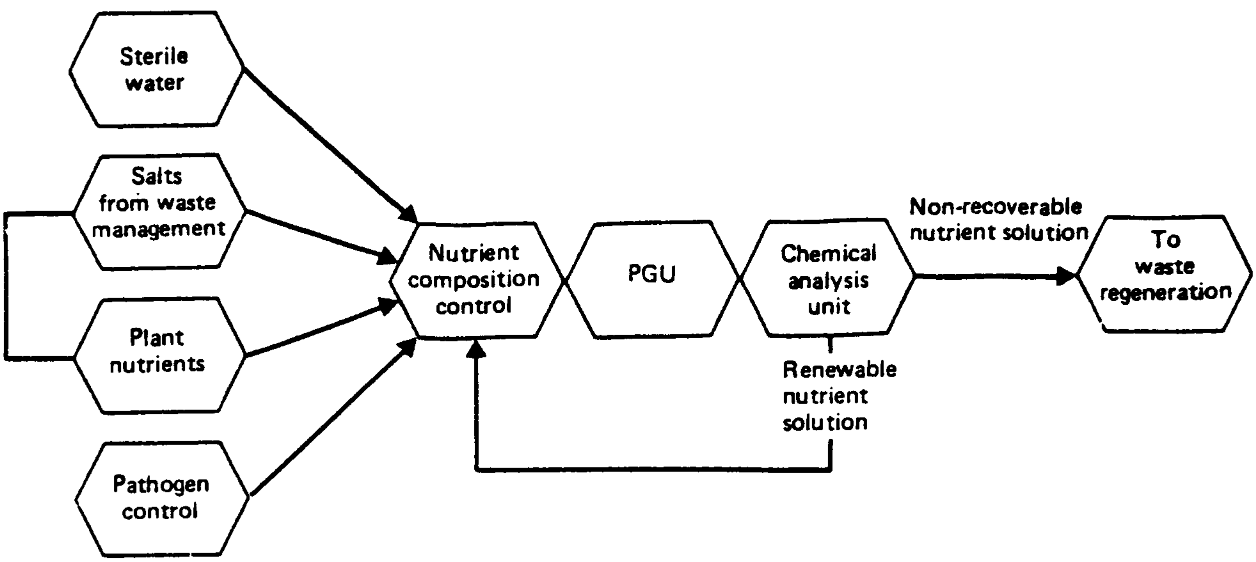


Figure 4.2-12. Nutrient Flow Diagram

4.2.4.1 Nutrients

Nutrient solutions are specifically formulated to promote optimum growth for each plant species. When crops are changed, nutrient solution compositions are adjusted. As nutrient solutions are recovered from PGUs, the compositions are analyzed. When analysis indicates low nutrient levels in solutions, make-up constituents are added as required. Ph is constantly adjusted and buffers added. Solution concentration is monitored through conductivity measurements that trigger water injections to make up for water lost to transpiration. Fungicides, bactericides, and other pest-control materials can be added to nutrient solutions to control specific problems. These photogenic organisms are identified by central microbial analyzer that receives periodic nutrient samples from each nutrient regeneration unit. When analysis indicates a maximum allowable buildup of contaminants, solutions are routed to waste regeneration system. Replacement solutions are added from the main nutrient supply reservoir.

4.2.4.2 Nutrient Circulation

The nutrient solution is supplied to all plant growth trays. An independent nutrient regeneration system supports every four PGUs to minimize crop failure in the event of a nutrient system failure. Nutrient solution is pumped to each tray at the rate of ½l/min for each square meter of plant growth area. Air is mixed with nutrient solution to ensure an adequate oxygen supply to roots. Air, with entrained nutrient solution, is removed by aspiration. Constant supply and removal of nutrient solution keeps root masses moist, aerated, and supplied with fresh nutrients.

Nutrient supply to each tray is pumped through injectors on swinging arms (fig. 4.2-13). This design permits direct nutrient injection into a telescoping spray tube inside the tray. The nutrient supply feed lines are are rotated aside when trays are removed for harvest, newly seeded trays are planted, and trays are shifted in position as crops mature.

Air from plant trays is passed through a water separator with recovered nutrient solution. The nutrient solution is returned to the nutrient supply system and the air is vented to module atmosphere.

Each PGU nutrient regeneration subsystem (fig. 4.2-14) is able to operate independently. Independent operation is limited by contaminant buildup or need to supply fresh makeup

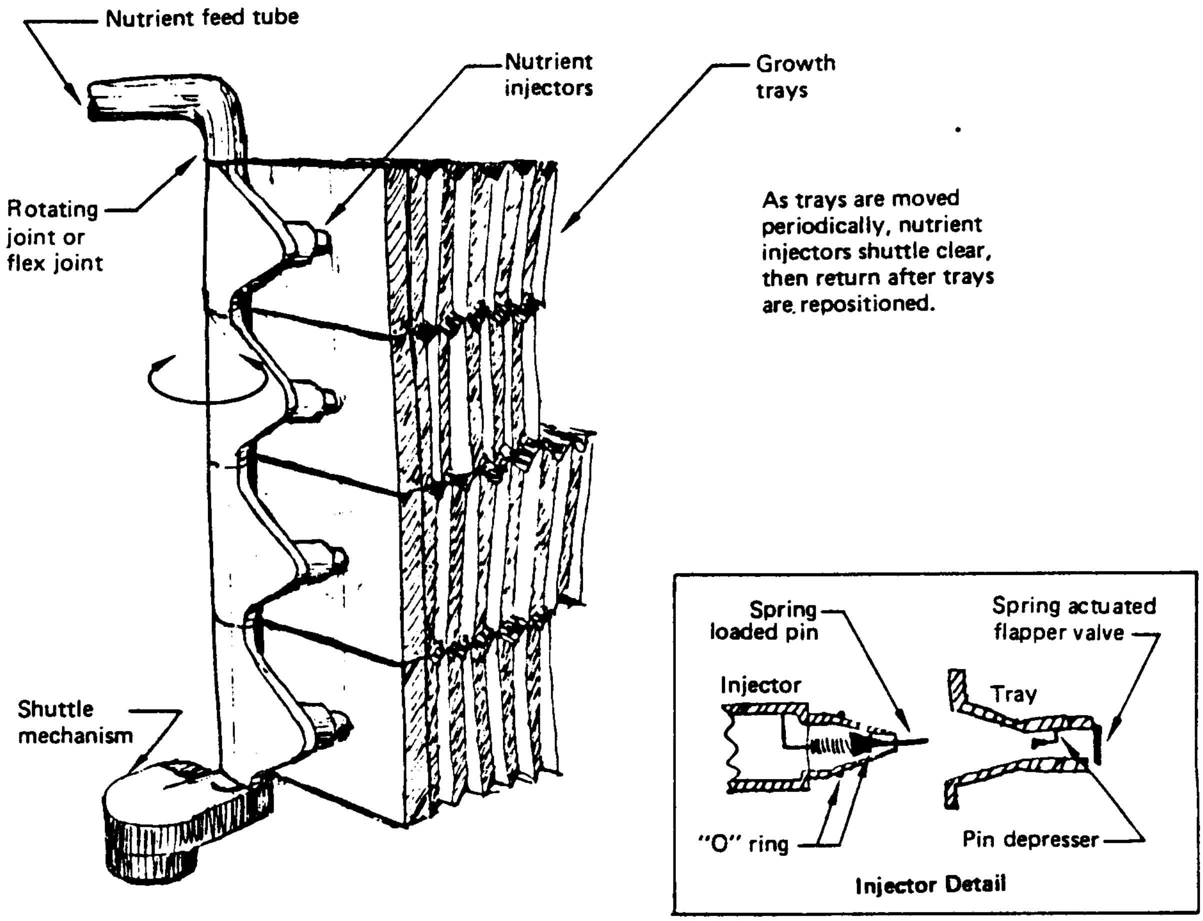


Figure 4.2-13. Nutrient Injection Detail

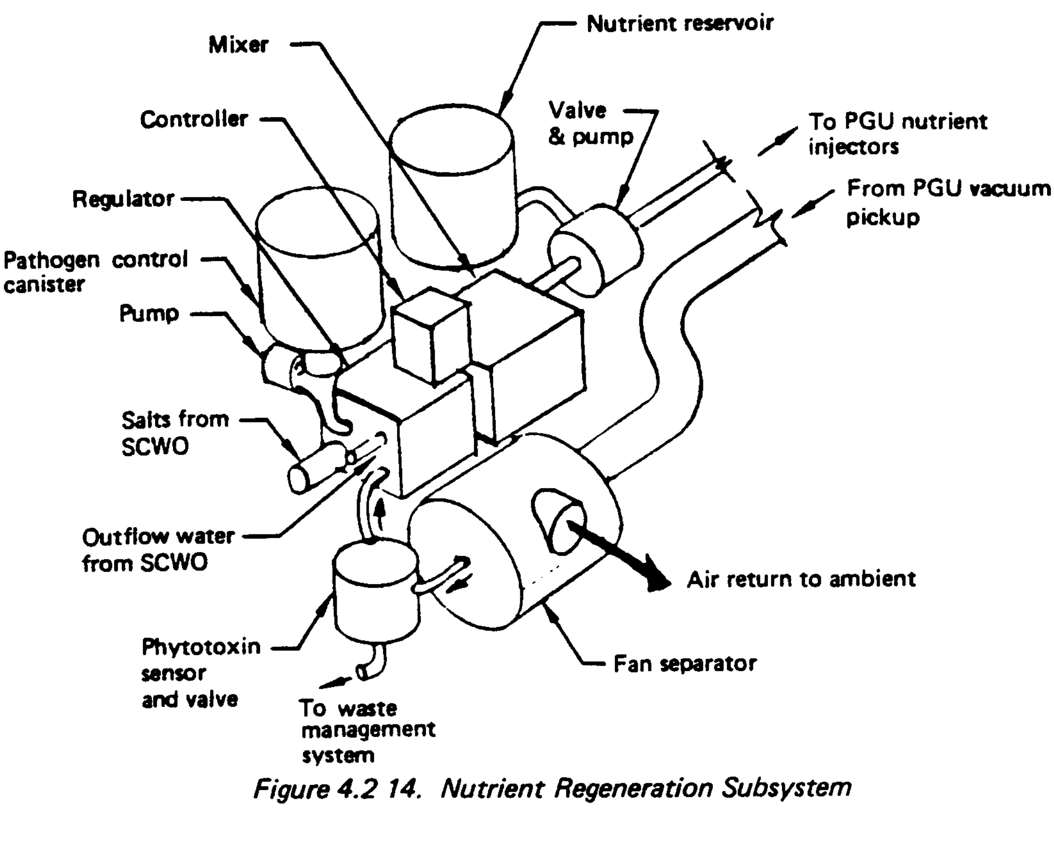


Figure 4.2 14. Nutrient Regeneration Subsystem

nutrient solution from the main supply reservoir. Isolation valves prevent major nutrient loss or contamination if problems develop anywhere in the nutrient supply system network. Cross-flow plumbing and control valves will allow adjacent PGUs to share nutrient supply if one supply subsystem fails. This redundancy will prevent crop loss.

4.2.4.3 Nutrient Contamination Control

Particles of root mass and any other particulate contaminants are filtered out of recovered nutrient solution before the solution returns to a supply tank. Dissolved contaminants are monitored. When maximum acceptable limits are reached, nutrient solution is dumped to the SCWO waste regeneration system and replaced with fresh solution from the main supply tank. Discarded solution is processed to recover nutrient salts for use in mixing fresh supply solutions.

4.2.4.4 Parts Listing

Table 4.2-5 lists major CELSS plant growth nutrient supply components.

4.2.5 Atmosphere Control

The CELSS module atmosphere is controlled for composition, pressure, and contaminant concentration. Atmosphere control flow is depicted in figure 4.2-15. Plant growth produces oxygen and uses carbon dioxide. Surplus oxygen is concentrated and stored. This oxygen can be directly fed to crew or waste regeneration system. Carbon dioxide is drawn from Space Station carbon dioxide scrubbing system or collected and stored from waste regeneration system gases. Contaminants enter the module atmosphere from plants, by out-gassing of plastics used in construction, by operation of powered equipment, by nutrient solution seepage, and by human entry into the module. Contaminants and concentrations are monitored and excessive levels are reduced by filtering and catalytic oxidation.

4.2.5.1 Composition and Pressure

The CELSS module nominal atmosphere is a standard pressure atmosphere with sea-level gas ratios. Some adjustment of carbon dioxide levels are made to optimize plant growth. Carbon dioxide levels are maintained at a nominal 750 ppm but may range from 250 to 2500 ppm. Nitrogen levels are kept near normal ratio. Stored gas reserves are used to

Table 4.2-5. CELSS Nutrient Supply System

Equipment	Quantity required	Size	Product in	Product out	Utility and power requirements	Comments
Main nutrient reservoir (bladder tank)	1	3.2 ft^3	Nutrient stock solution ⟶		Support structure	Volume approximately 4 times system flow rate per minute
Tier unit reservior (bladder tank)	12 (24)	.3 ft^3 (8.03" x 8.03" x 8.03")	Nutrient ⟶ solution		Support structure	12 = 1 per 2 tiers (24) = 1 per tier
Pump main tank	1	3 - 6 gal/min 10x12x16 1920 in^3	Nutrient ⟶ solution		Either 28 VDC 115 VAC 200 W	Replenish tier unit tank as required
Pumps tier tanks	12 (24)	.3 - .4 gal/min 4x6x8 192 in^3	Nutrient ⟶ solution		Either 28 VDC 115 VAC 40 W	
Quantity sensor	24 (48)					Controls replacement of lost quantity in tier tank
Air/water separator	12 (24)	8" dia x 7" 351.9 in^3	Air and nutrient solution	Air fluid nutrient solution	Either 28 VDC 115 VAC 40 W	Returns fluid nutrient to system
Filter	12 (24)	6" dia x 2" 56.5 in^3	Nutrient solution particulate material	Nutrient solution solid waste		Strain out particulate matter, root particles, etc.
Probes PH O_2 Conductivity ION (9)	 24 24 24 216	.25" x 4"				Analyze nutrient solution
Injectors	192	.5" x .6"	Replenishment ⟶ solutions			Maintain proper nutrient concentration
Monitor probes PH O_2 ION (3)	 24 24 72	.25" x 4"				Check proper nutrient concentration
Nutrient supply arm	192	2.5" x 3.0" x 7" 53 in^3	Nutrient and air			1 per growth tray

Table 4.2-5. CELSS Plant Growth Nutrient Supply

Equipment	Quantity required	Size	Product in	Product out	Utility and power requirements	Comments
Solenoid actuators (arm)	192	2" x 2" x 3" 12 in^3			28 VDC 200 W	Intermittent operation
Flow regulator	192	5" high x 4" wide x 2" deep 40 in^3	Nutrient solution	→	Either 28 VDC 115 VAC 40 W	Control nutrient flow rate to each tray
Check valve	192	2" high x 4" wide x 6" deep 48 in^3	Nutrient solution	→		To each tray
Injector	192	.5" x 6"				Inject nutrient into tray
By pass valve	24	4" x 4" x 3" 48 in^3	Nutrient solution	→		To tray or dump to SCWO
Solenoid fill valve	24	5" x 4" x 2" 40 in^3	Nutrient solution	→	28 VDC 200 W	Intermittent works with quantity sensors to keep tier tanks full

maintain module pressure and ensure a constant source of constituent gases. Nitrogen and carbon dioxide are by-products from the waste regeneration system that aid in maintaining the atmosphere. Additional carbon dioxide may be gained from Space Station atmosphere control.

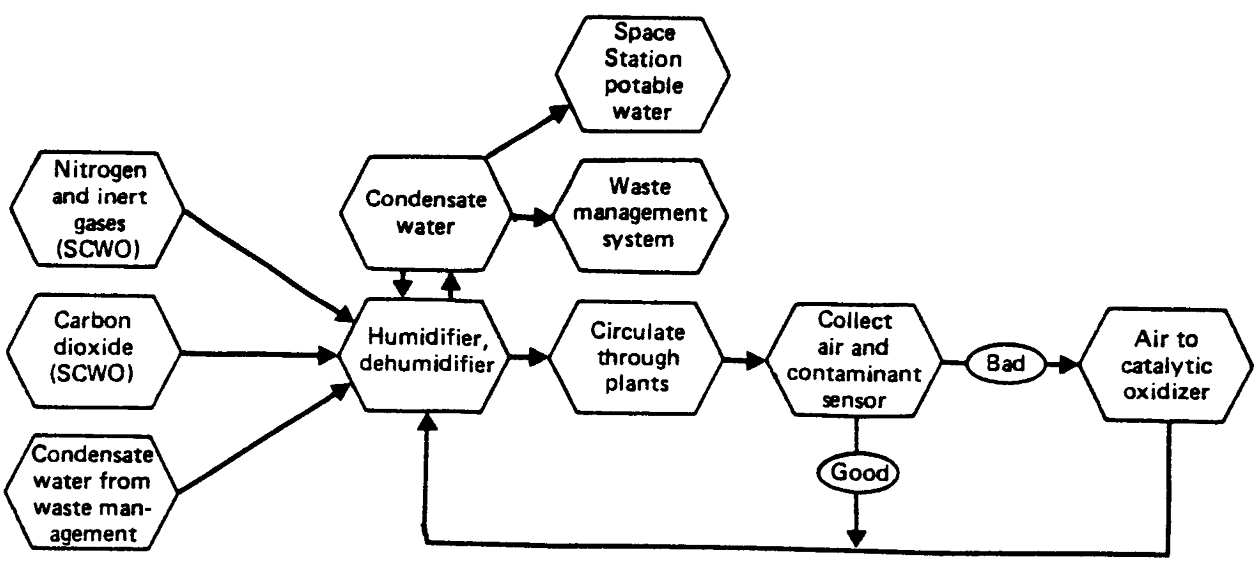


Figure 4.2-15. Air Circulation Flow Diagram

Oxygen produced by plant growth is used in waste regeneration (sec. 4.2.6) and for Space Station crew oxygen supplies. An oxygen scrubber is used to remove surplus oxygen produced by the plants. This oxygen is stored and used in the waste regeneration SCWO reactor or added to Space Station supply.

4.2.5.2 Contaminant Control

Contaminants enter CELSS atmosphere from most equipment, materials, and processes in the module. Growing plants emit contaminants as well as producing oxygen. Outgassing of materials and operation of powered mechanisms may generate a variety of gaseous and vapor contaminants. Seepage and subsequent evaporation of nutrient solution adds corrosive salts and some particulate material.

CELSS air circulation is used to transport contaminants to removal equipment. Passing air through filters removes particulate matter and some contaminant gasses. Bleeding off air for the catalytic combustion system destroys or converts contaminant gasses into less noxious substances. Periodic oxidation of remaining contaminants through the waste regeneration system removes remaining CELSS atmospheric contaminants (fig. 4.2-16).

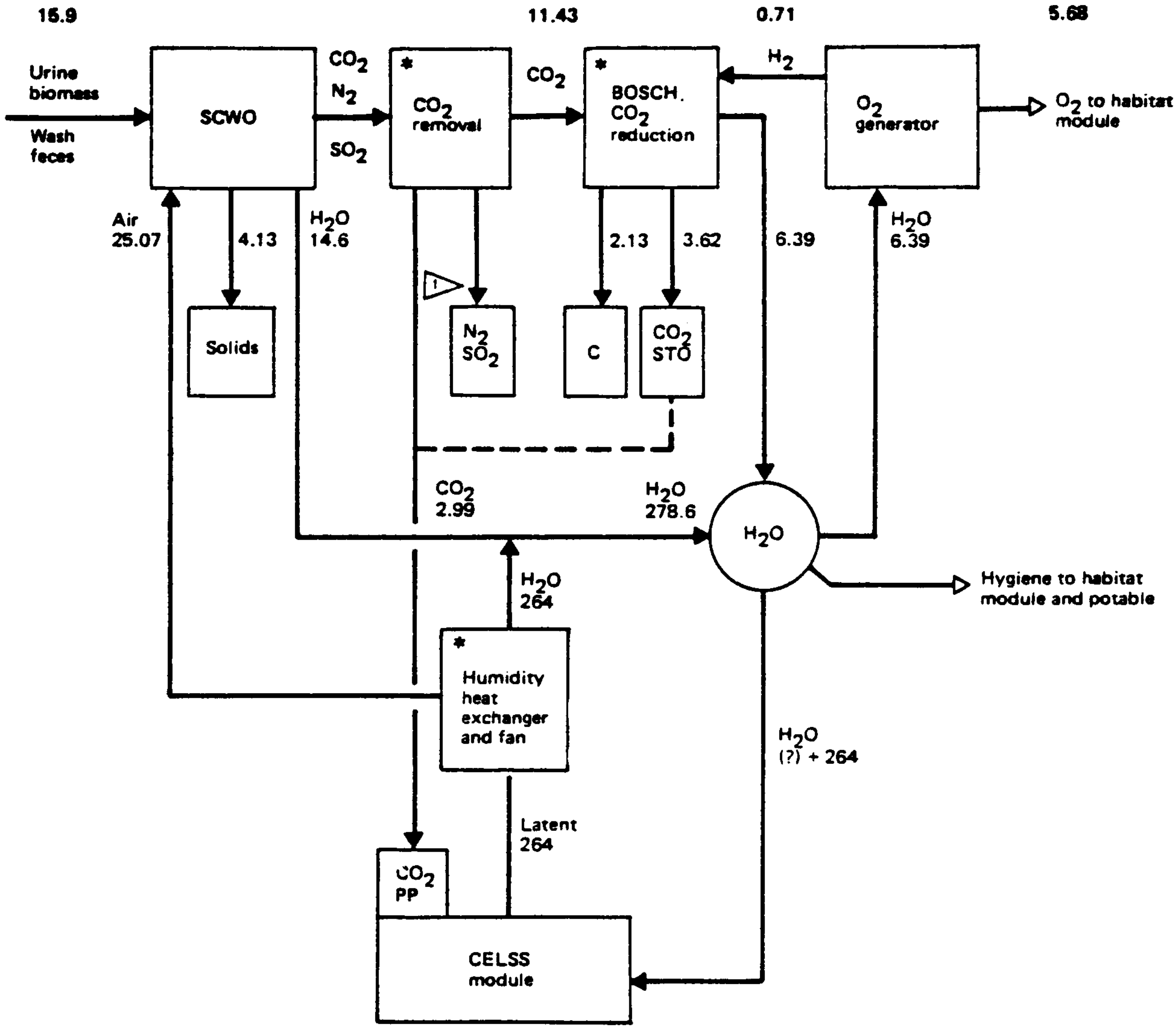
4.2.5.3 Parts Listing

Tables 4.2-6 lists major CELSS atmosphere control system components.

4.2.6 Waste Regeneration

All solid and liquid wastes produced by the CELSS operation along with some or all the waste from two crew members are processed through the SCWO waste regeneration unit. This process uses the unusual properties of steam under high pressure and temperature to oxidize all organic products to salts, water, carbon dioxide, and nitrogen. Oxidation products (mainly salts) are reclaimed for replenishing plant nutrient materials and Space Station stores.

In operation, solid wastes are finely ground and mixed with liquid wastes and waste water. The resulting slurry is processed through the SCWO unit reactor. Salts are salvaged to replace nutrients, steam is condensed for potable water, and gases are stored for atmosphere control. Unusable solid waste residue is collected and stored for eventual disposal (fig. 4.2-17).



Run through trace contaminant control loop N_2 back

Figure 4.2-16. Atmosphere Contaminant Control

4.2.6.1 Biomass and Nutrient Waste

Plant waste, totalling approximately 7 lb/day of nonedible plant material, is ground very fine, mixed with waste nutrient solution or other liquid waste and water (as required) to form a slurry. Electric power is used to heat the slurry; the slurry is then pumped to the SCWO reactor (fig. 4.2-18 and 4.2-19). Preheated air and oxygen are added under high pressure causing the waste material to oxidize. Supercritical water from the oxidation process is routed to heat exchangers to reduce preheat electric power. Water and entrained carbon dioxide and nitrogen gases are subsequently separated. The water is added to potable water stores and gases are stored for atmosphere control (sec. 4.2.5.1).

Table 4.2-6. CELSS Atmosphere Control

Equipment	Quantity required	Size	Product in	Product out	Utility and power requirements	Comments
N_2 storage tank	1	10" dia 30" long (2356 in^3)	N_2 →			Store for addition to CELSS atmosphere
Pump	2	7" dia .10" long (385 in^3)	N_2 O_2 →		28 VDC 115 VAC 150 W	Pumps N_2 and O_2 to storage tanks
Electric solenoid valves	6	5" high 4" wide 2" deep (40 in^3)			28 VDC 115 VAC 50 W	
SCWO	← See SCWO or waste →					
CO_2 removal	1	10" x 12" x 14" (1680 in^3)	SCWO combustion gas	CO_2 N_2 SO_2		Sends CO_2 to module atmosphere or storage
BOSCH CO_2 reduction	1	12" x 10" x 10" (1200 in^3)	CO_2 H_2	C CO_2 H_2O		
O_2 scrubber	1	8" dia 10" long (503 in^3)	Module atmosphere	O_2 and air		Store O_2 in tank
O_2 storage tank	1	12" dia 36" long (4072 in^3)	O_2 →			Store O_2 for SCWO or Space Station use

Note: Basic humidity control is part of temperature control – circulation of air during non SCWO operation is part of temperature control air movement

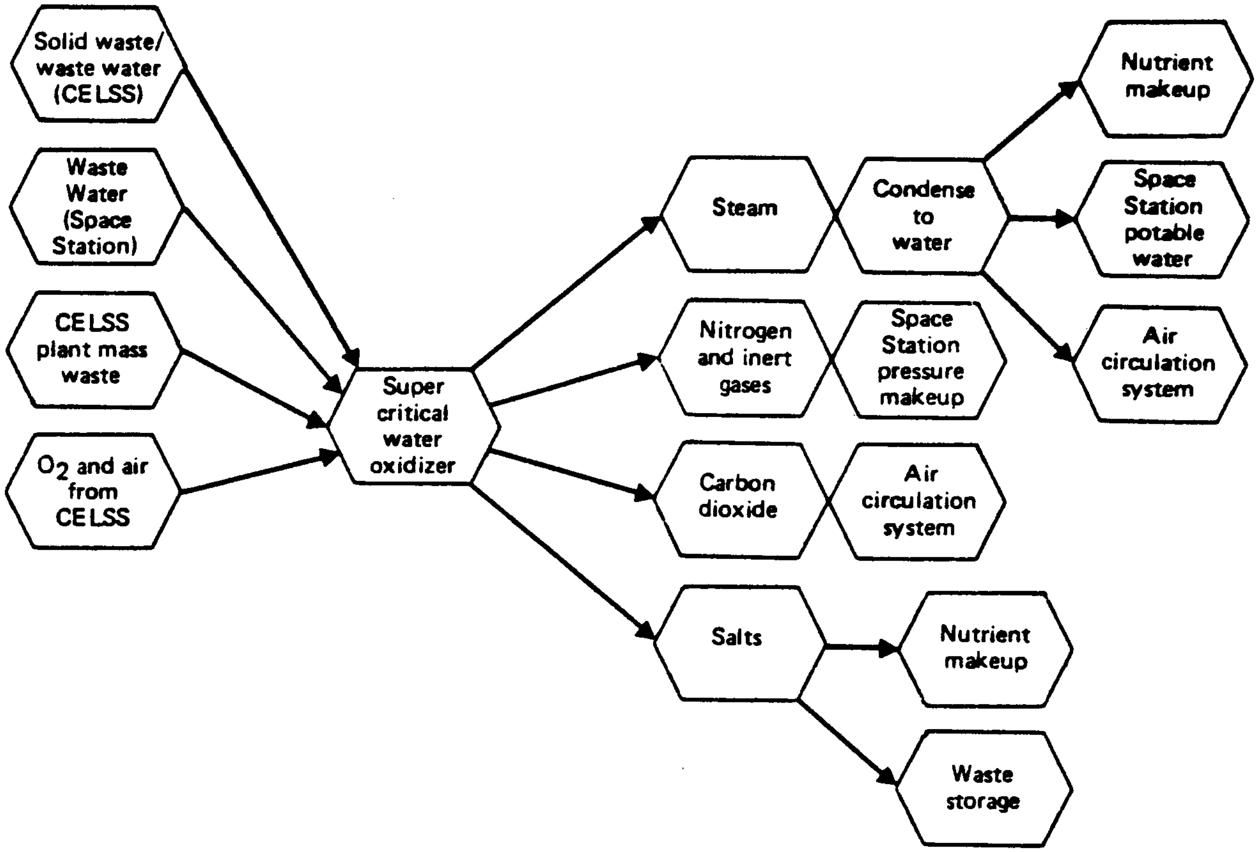


Figure 4.2-17. Waste Management System Flow Diagram

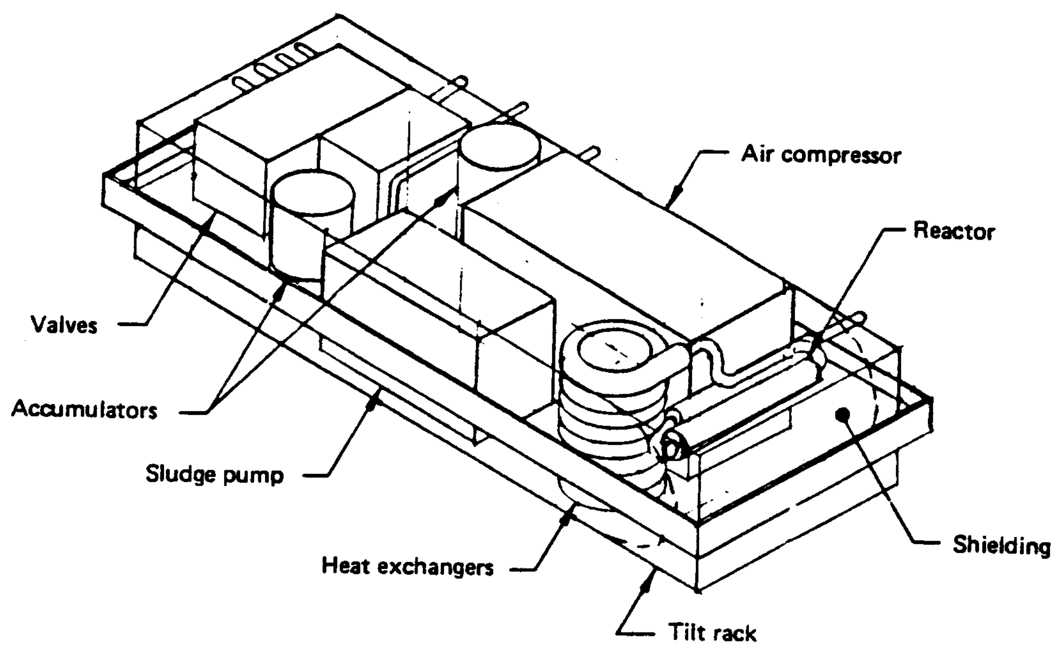
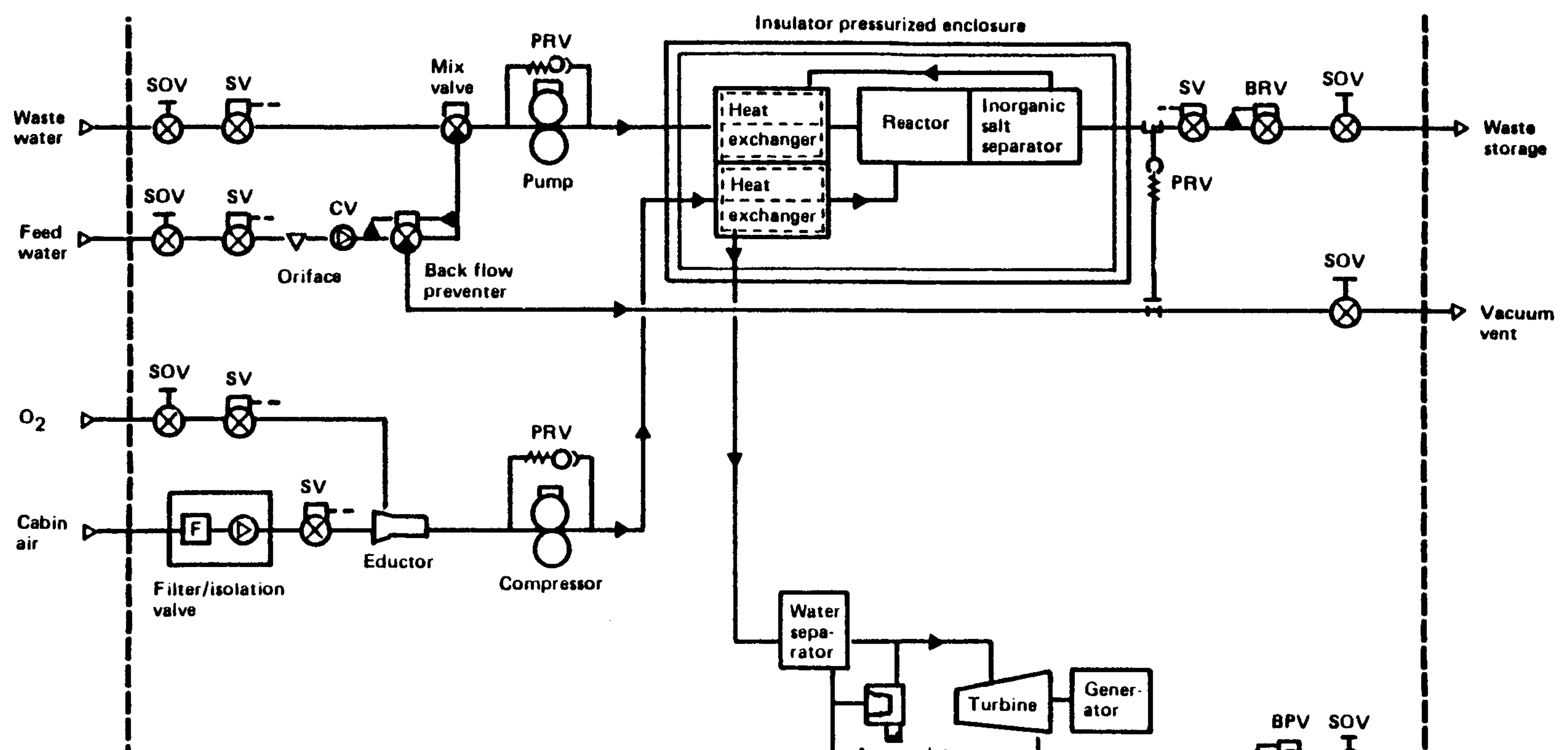


Figure 4.2-18. Super Critical Water Oxidizer



Legend:

Item	Description
Accum	Accumulator
BPR	Back pressure regulator
CV	Check valve
F	Filter
Gen	Electrical generator
PRV	Pressure relief valve
Q	Quantity sensor
SOV	Shut off valve (isolation)
SV	Solenoid valve
Turb	Gas turbine
Wtr sep	Water separator (mech or passive)

Figure 4.2-19. Super Critical Water Oxidation Space Station Application

Solid oxidation products are processed in the inorganic salt separator. Nutrient salt materials are recycled in makeup nutrient solution. Unusable solid waste residue is stored for later disposal.

4.2.6.2 Space Station Waste

Solid and liquid wastes from two Space Station crew members, approximately 10 lb/day, are moved to the CELSS module and processed through the SCWO unit. They are treated in the same manner plant wastes are processed. Solids are ground and mixed with liquid to make a slurry, oxidized, and the products of oxidation reclaimed for recycling. These wastes may include human fecal wastes and Space Station process wastes.

4.2.6.3 Other Waste

Other waste material includes atmosphere contaminants and contaminant control filter material. Atmosphere control filters are ground up with other oxidizable waste (e.g., garbage, clothing) noncombustible waste or waste that would create toxic hazards when oxidized are separated from routine waste regeneration. Not used in the waste regeneration system are broken or discarded equipment, such as metal parts and burned-out fluorescent tubes. This material is added to the nonreusable residue from the oxidation process and disposed of in accordance with Space Station procedure.

4.2.6.4 Parts Listing

Table 4.2-7 lists major CELSS waste regeneration system components.

4.2.7 Food Processing

Food processing includes harvesting mature plants, separating food from inedible waste, and storing collected food (fig. 4.2-20). Food processing starts when a plant growth tray is removed from PGUs.

4.2.7.1 Food Harvest

The trays with mature plants are removed from the PGU by the harvest robot, (sec. 4.2.8). The robot transports each tray to the harvest unit where tray end caps are removed. A processing robot then positions each tray into the harvest machine (fig.

Table 4.2-7. Super Critical Water Oxidation System Component Listing

Equipment	Quantity required	Size	Product in	Product out	Utility and power requirement	Comments
Reactor	1	2.5" dia x 20" long 98 in^3	Slurry and O_2 or air	Inorganic salts and steam, CO_2, N_2	Pressure and temperature sensors 5639 W for 5 minutes	3700 psi operating pressure 700°F operating temperature
Inorganic salts separator	1	2" dia x 11" long 34.6 in^3	Inorganic salts, steam, CO_2, N_2	Inorganic salts by pass others to heat exchangers	Sensors	
Liquid/ liquid heat exchanger	1	12" dia x 4" high 452.4 in^3	Slurry is heated, super-critical water is cooled		Note: Pressure on slurry maintained by sludge pump	Double tube spiral coil
Liquid/ gas heat exchanger	1	12" dia x 4" high 452.4 in^3	O_2 or air is heated, super-critical water is cooled			Double tube spiral coil Should be downstream of liquid/liquid heat exchanger
Air compressor	1	15" high x 30" wide x 13" deep 5850 in^3	Cabin air or O_2	Compressed air or O_2	Either 28 VDC 115 VAC 812 W	
Accumulator	2	7" dia x 11" high 423.3 in^3	Condensate storage		Quantity sensor	
Manual shut-off valve	7	7" high x 4" wide x 5" deep 140 in^3				Isolate system loops for maintenance
Mixing valve	1	7" high x 4" wide x 5" deep 140 in^3	Slurry and hygiene water	Reactor ready slurry	Slurry composition 28 VDC	Controls concentration of slurry by adding hygiene water
Electric solenoid valve	8	5" high x 4" wide x 2" deep 40 in^3			28 VDC or 115 VAC	Flow regulation (on/off cycles)
Back pressure valve	4	3" high x 4" wide x 4" deep 48 in^3			28 VDC or 115 VAC	Prevents contamination of hygiene water by slurry

Table 4.2-7. SCWO (Continued)

Equipment	Quantity required	Size	Product in	Product out	Utility and power requirement	Comments
Turbine/ generator	1	24" high x 24" wide x 36" deep 20,736 in^3	High pressure steam	Low pressure steam and 1 kW of electricity	Pressure, speed, voltage and current sensors	May or may not be used
Fan separator	2	7" dia x 6" high 230.9 in^3	Water, CO_2, N_2	Water, CO_2, N_2		Separates reactor outflow water from CO_2 and N_2
Sludge pump	1	10" high x 13" wide x 20" deep 2600 in^3	Reactor ready slurry	3700 psi slurry	115 VAC anticipate large power requirements 373 W	Approximately 20 lbs/ batch in one hour
Check valve	1	2" high x 4" wide x 6" deep 48 in^3				Prevents slurry backflow through sludge pump
Control power		Total volume 31,293.5 in^3			6 W x 6 units = 36 W	

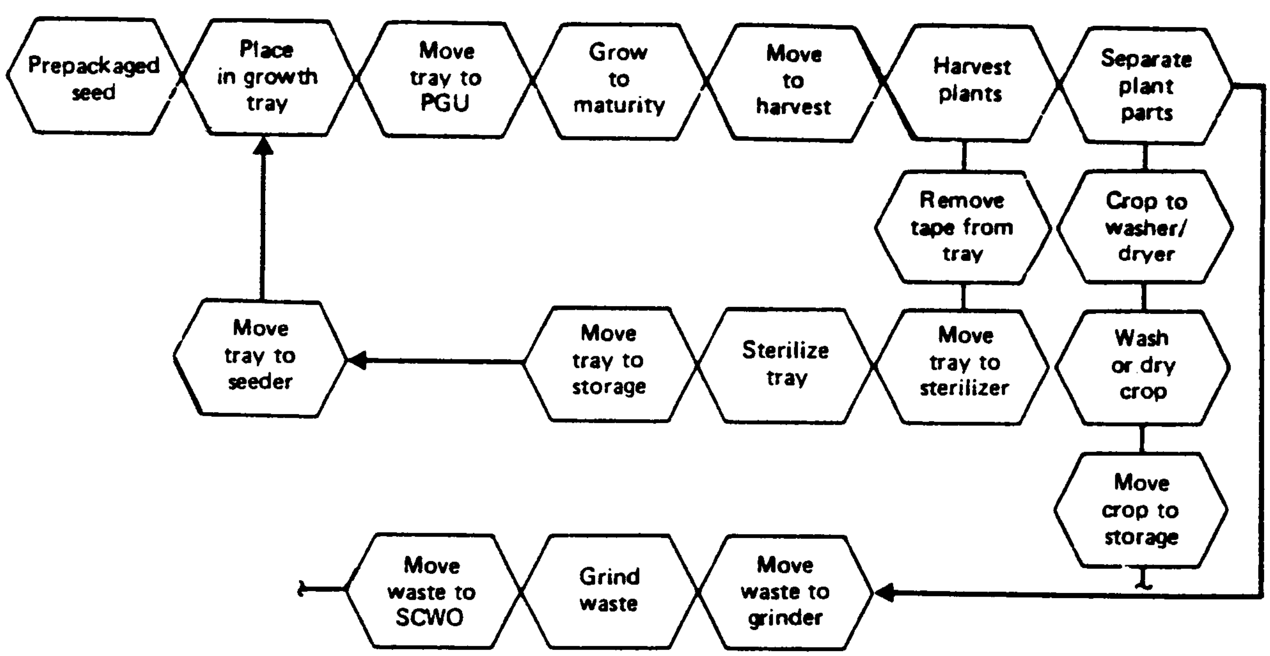


Figure 4.2-20. Plant Flow Path Through CELSS

4.2-21). A cutter at the entrance clips plant stems close to the tray surface while the roots are pushed out of the tray by the robot arm (sec. 4.2.8.3).

Air flow through the tray and harvest area pulls the loose crop, stems, and roots into the harvest chamber. All material is drawn into an air pump and expelled into CELSS food processor separation chamber. Here, a cross-flow of air separates crop from chaff by deflecting less dense biomass waste from direct passage through the chamber. Waste and crop are gathered into separate containers for subsequent processing.

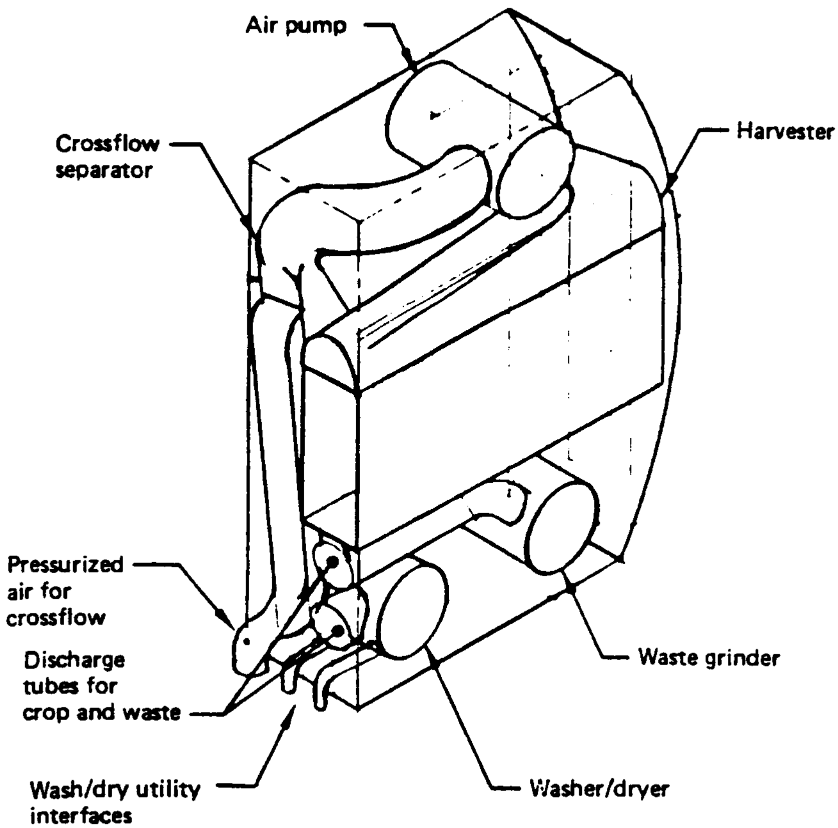


Figure 4.2-21. CELSS Plant Harvester

4.2.7.2 Food Processing

Harvested food is collected into a washer/dryer (fig. 4.2-21). Dust, dried nutrient solution, and any other contaminants are rinsed off in a water bath. The washed crop is then dried in a flow of warm, dry air. The edible material is collected and stored until needed for space Station consumption. A crew member will enter the CELSS module, as required, to transfer food supplies back to crew quarters.

4.2.7.3 Waste Material

Waste material collected during harvest operations are ground and stored pending additional processing. Finely ground waste is mixed with water to form a slurry that is pumped into the SCWO reactor for direct waste regeneration (sec. 4.2.6.1). The waste slurry may also be processed for cellulose conversion to edible biomass.

4.2.7.4 Cellulose Conversion

In order to make use of the inedible biomass left over from the crop harvest, it will all be run through the processor until finely ground. The inedible biomass can then be converted into sugars that, in turn, can be fermented for use as a chemical feed stock or edible protein.

Conversion is accomplished by means of hydrolysis of the cellulose material by cellulase or cellulolytic microorganisms. When hydrolysis is complete, the sugars that are a product of the conversion can be used as an energy source to aid in the fermentation process that follows. Alcohols, ketones, hydrocarbons, fibers, etc. are examples of some of the products derived from cellulose conversion.

Anaerobic, mesophilic, cellulolytic bacteria, which survive in medium temperatures around 98.6^{o}F, from natural aquatic environments are among the microorganisms that have been isolated. These microorganisms are effective in converting cellulose into single-cell protein and ethanol through yeast fermentation.

Fungi are another group that can convert carbohydrates. Temphe, fungal mycelium, grown on soybean cakes and wheat cakes is used in Southeast Asia as a high-protein food source. Fungi species are known that operate under nearly any temperature and humidity combination expected on Space Station. Fungi can also break down complex carbohydrates not attacked by bacteria. For example, along with cellulose, which is a carbohydrate, there exists a noncarbohydrate called lignin that also acts as a structural component in higher plants. Lignin has no known human food value but is assimilated by many varieties of fungi, some of which may be edible.

4.2.7.5 Parts Listing

Table 4.2-8 lists major CELSS harvester and food processing equipment.

Table 4.2-8. CELSS Harvester Components

Equipment	Quantity required	Size	Product in	Product out	Utility and power requirements	Comments
Plant harvester	1	11" wide x 35" tall x 60" deep	PGU trays with plants, pre-dried from robot	Dissociated plant mass, roots and crop	Suction air provided by air pump 28 VAC, 300 watts	Needs to be vibration insulated as it is a vibration source
Air pump	1	15" dia x 18" long	Dissociated plant mass, roots and crop	→	28 VDC, 400 watts	Diaphragm type, sized to accommodate potatoes
Crossflow separator	1	8" wide x 40" tall x 30" deep	Dissociated plant mass, roots and crop	Separated crops from plant and root masses	Pressurized air for cross-flow air currents (from station)	Separates by deflecting lower mass/greater surface area from higher mass/lower surface area particles
Washer/ dryer	1	15" dia x 18" long	Crops	Washed and dried crops go to robot	Warm air from station Washing water which is potable return water 28 VDC, 200 watts	Washes and/or dries crops only as needed for an individual crop, i.e. wheat might only be dried, potatoes might be washed and dried
Waste grinder	1	15" dia x 18" long	Plant and root mass	Finely chopped plant and root mass to SCWO via robot	28 VDC, 300 watts	
Motor (Harvester, see page 1)	1		Electric power	Power to actuate harvester mechanism	28 VDC, 300 watts	Vibration isolation required (see Plant harvester, page 1)
Motor (Air pump, see page 1)	1		Electric power	Power to actuate air pump	28 VDC, 400 watts	Diaphragm type, sized to accommodate potatoes (see Air pump, page 1)
Cabling	1					Electric power to motors
Ducting	1		Air →	→		Air flow routing, etc., crop flow

4.2.8 Robotics

CELSS module operation is fully automated. Robots are a key automation element performing all planting, harvesting, and waste handling operations. Space Station crew members normally enter the module only for removing food supplies or to perform maintenance or repair functions.

Two robots are mounted on a pair of tracks running full length of the module. One track is above and one is below the center aisle (fig. 4.2-22). Each robot is on a column between the two tracks and can move up or down between tracks. Longitudinal travel is made possible by a powered roller platform riding on each rail.

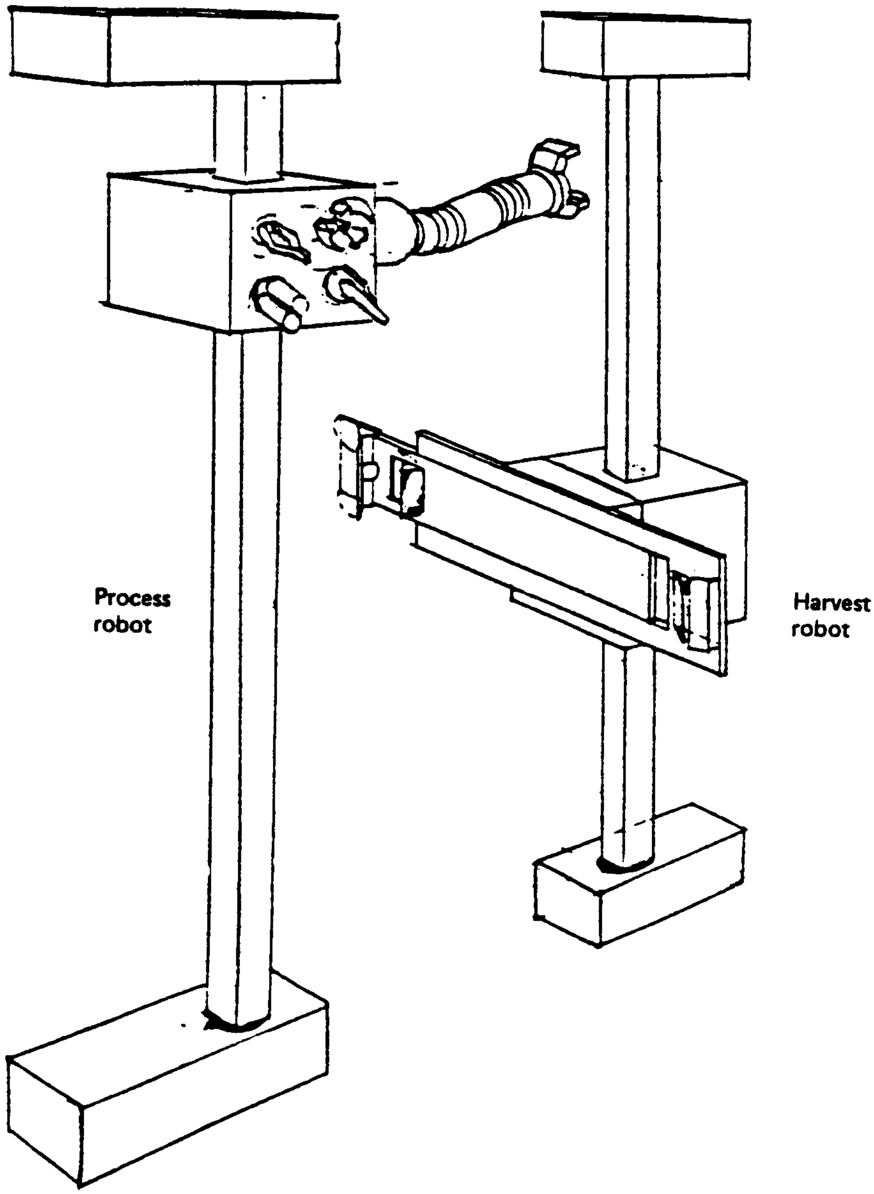


Figure 4.2-22. CELSS Robots

The harvest robot handles plant trays in the PGUs, planting newly seeded trays and harvesting mature plant trays. It also transports trays to he plant harvesting and processing equipment.

The process robot handles the tray after the harvest robot positions it in the harvest equipment.

Reseeding trays with new seed mats is accomplished by the process robot operating the seeder equipment. It also moves seed mat cartridges into position when replacing an emptied cartridge.

The following list outlines robot major functions operating the plant growth and harvest equipment.

CELSS Robot Functions

1. Take a clean tray from tray storage area.
2. Stretch tray to its full length.
3. Insert tray into tray seeder.
4. After seed tape is put on tray, remove tray from seeder.
5. Compress tray.
6. Insert tray into PGU.
7. Using optical and electrical resistance sensors, monitor plant growth; health; and nutrient, moisture, and light levels.
8. Remove mature plant tray from PGU.
9. Compress tray.
10. Remove end caps from tay.
11. Insert tray into harvester unit.
12. As tray enters unit, operate a plunger to push plant and root masses further into harvester.
13. After plant and root masses are in harvester, remove tray.
14. Collect crop and waste products from their appropriate tubes.
15. Compress tray fully.
16. Put tray in tray sterilizer.
17. Put crops in appropriate storage bins.
18. Put waste products into waste management system
19. Remove sterilized tray from tray sterilizer.
20. Put tray in tray storage area.

4.2.8.1 Robot Support Structure

Both robots are mounted on a pair of longitudinal rails running the full length of the CELSS module. Each robot unit is installed on a column between the rails. Motion along the rails is accomplished by powered roller platforms on each end of the columns. The robot units move up and down the column to gain access to all equipment in the module.

4.2.8.2 Harvest Robot

The harvest robot has two extendable arms with tray-grasping latches at each end. These arms hold a tray in either compressed or extended conditions and can extend or compress a tray as required. One arm faces each end of the module to handle trays oriented in either direction. The supporting column rotates the position of the extendable arms to either side of the aisle to service all PGUs.

4.2.8.3 Process Robot

The process robot handles plant trays through all operations of the food harvest and process equipment and tray seeder. It removes tray end caps when trays arrive in the processing area. After an opened tray is inserted into the harvest equipment, the process robot moves it past the stem cutter and forces root mass out and into the harvester biomass collection chamber.

Tray preparation and seeding is the process robot's second major activity. Empty, harvested trays are cleaned, sterilized, and positioned in the seeder. After completion of seeding operations, the process robot reattaches end caps and places trays in ready storage. This robot services the seeder with loaded seed mat cartridges as required after each set of the 18 trays is processed.

4.2.8.4 Parts of the Listing

Table 4.2-9 lists major CELSS robot components for both robots.

4.2.9 Module Packaging

CELSS module packaging is shown in figure 4.2-23. The common module shell determines dimensions and gross volume for packaging the CELSS design. The module

Table 4.2-9. CELSS Robot Components

Equipment	Quantity required	Size	Product in	Product out	Utility and power requirements	Comments
Track	2	27' long x ?			Support structure in module	Longitudinal track "above" and "below" aisle way. Robot travels along track
Pedestal	2	4" x 4" x 11'				Supports and guides planting and harvest power units
Trucks (pedestal)	4	4" x 6" x 18"				Supports and moves power units(s) to required position along aisle
Planting power unit	1	14" x 16" x 18"				
Tele-scoping tray hand-ling arms	2	2" x 8" x 6.8' (extended)				Insert, remove, and transport plant trays
Motor(s), reversing	2		Electric power	Motion	Either 28 VDC 115 VAC 40 W each	Extend and retract tele-scoping arms
Motor reversing	2		Electric power	Motion	Either 28 VDC 115 VAC 40 W each	Move arms to insert or extract trays
Actuator(s)	4					Operate tray grippers on telescoping arms
Power unit motor (planting)	1		Electric power	Motion	Either 28 VDC 115 VAC 140 W	Move power unit "up" and "down" pedestal
Pedestal motor(s)	2		Electric power	Motion	Either 28 VDC 115 VAC 140 W each	Rotates pedestal (power unit faces other side of aisle)
Motor(s), truck(s), pedestal	4		Electric power	Motion	Either 28 VDC 115 VAC 160 W	Move pedestal(s) along tracks
Harvest and utility power unit	1	16" x 16" x 18"				
Arm (Harvest and utility)	1					Push biomass from tray into harvest machine, move crop to storage, perform operating functions, etc.

Table 4.2-9. CELSS Robot (Continued)

Equipment	Quantity required	Size	Product in	Product out	Utility and power requirements	Comments
Motor(s)	(1 for each ° of freedom) 6		Electric power	Motion	Either 28 VDC 115 VAC 40 W each	Move arm to harvest crop, handle tray, etc.
Actuator	1					Operate robot "hand" (or tool)
Tools (hands)	5 ?					Various tools for different robot tasks
Power unit motor (Harvest and utility)	1		Electric power	Motion	Either 28 VDC 115 VAC 140 W	Move power unit "up" and "down" pedestal

primary structure needs only minor changes for this packing scenario (i.e., removal of unneeded features or creating new pierce points for fiber optic cable entry). The module secondary structure (interior) is organized for specific CELSS equipment. Working area height is increased to provide efficient volume use for plant growth. PGU structures are installed to support plant growth trays and lighting systems. Tracks are installed for robot mobility. Rack support structures are designed specifically for each CELSS system.

4.2.9.1 Module Primary Structure

The Boeing-proposed Space Station common module is used as primary structure in this packaging scenario. Available volume is fixed by an interior diameter of 164 in and a length of approximately 35 ft. Changes to the common module include elimination or radial berthing ports and one end berthing port. Special outer shell pierce points are added for fiber optic cable entry (sec. 4.2.2.2).

4.2.9.2 Module Secondary Structure

The CELSS module interior structure is customized for specific plant growth equipment and requirements. Support bulkheads are added from plant tray supports; frames are installed to support lighting luminaries. Nutrient supply system tanks, pumps, and plumbing are installed adjacent to PGUs in V-shaped areas between light panels. Rails are installed down the aisle between PGUs for robot mobility. An alcove exists at the

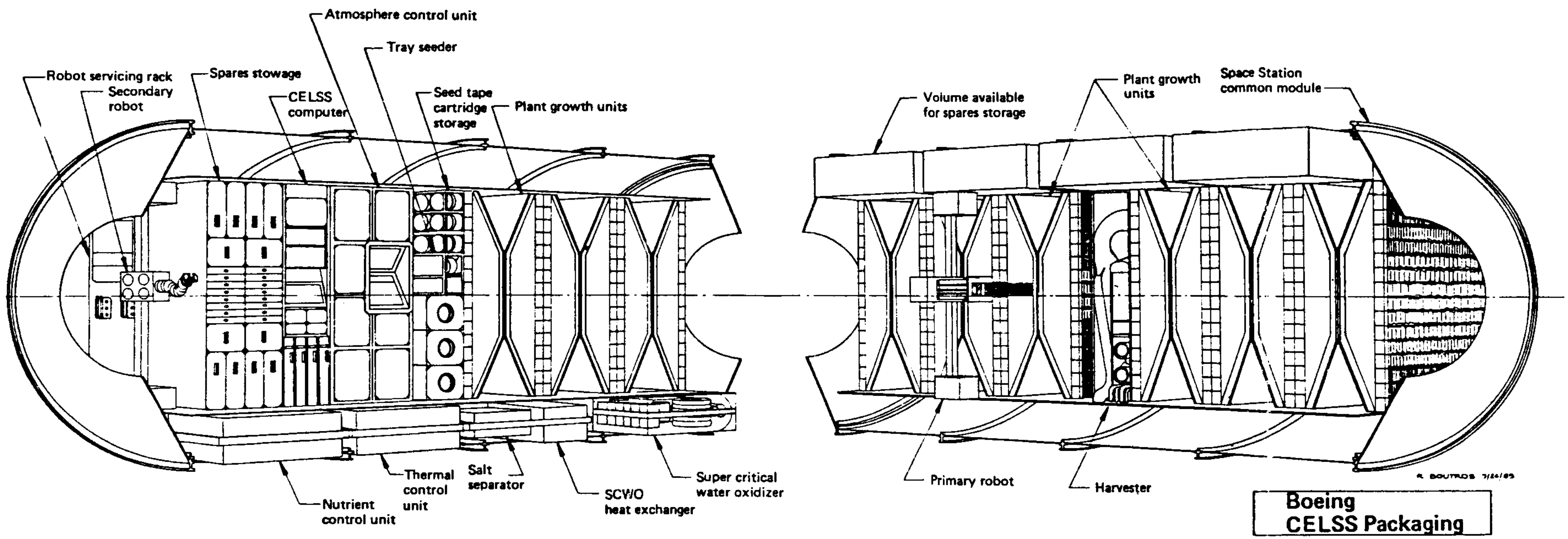


Figure 4.2-23. CELSS Module Packaging

robot servicing station to allow robot storage out of the aisle. The support structure for other systems is installed as required for each unique item. Air cooling ducts are installed along the rows of PGUs. Areas under the flooring and over ceiling hold ECLSS, storage bins, nutrient supply tanks, and waste regeneration system. These units are all on hinges to facilitate maintenance. All of the secondary structure is CELSS unique.

Material selection for CELSS module secondary structure is complicated by the highly corrosive environment created by nutrient solutions. Metals, including stainless steel, corrode. Plastics are used for much of the secondary structure adjacent to the PGUs for corrosion resistance. Plastics are considered a viable candidate for other support structures for weight savings. Metal interior module structure is limited to corrosion-resistant alloys with protective coatings. Plastic structure material is selected for stability, strength, and compatibility with CELSS materials and processes.

4.3 SYSTEM INTEGRATION

Packaging CELSS in one module amplifies each system's effect on and interaction with other systems. No system design can be considered alone without considering its interaction with other systems. Examples of system interaction and factors influencing design are illustrated in figure 4.3-1 and the following sections.

4.3.1 Lighting System Integration

Lighting system conceptual design include-

a. Collected solar rays.
b. Collected solar rays supplemented with artificial light sources.
c. Artificial light sources.

The first calculations of electrical power required (75 kW to provide efficient growth illuminations see sec. 4.3.2.2) eliminated artificial illumination for total plant lighting. Electrical power in excess of 75 kW exceeded any reasonable power allocations. Collected solar ray lighting only for 60 min followed by 30 min of darkness may not promote normal plant growth. Thus, solar lighting alone is not considered an optimum design alternative.

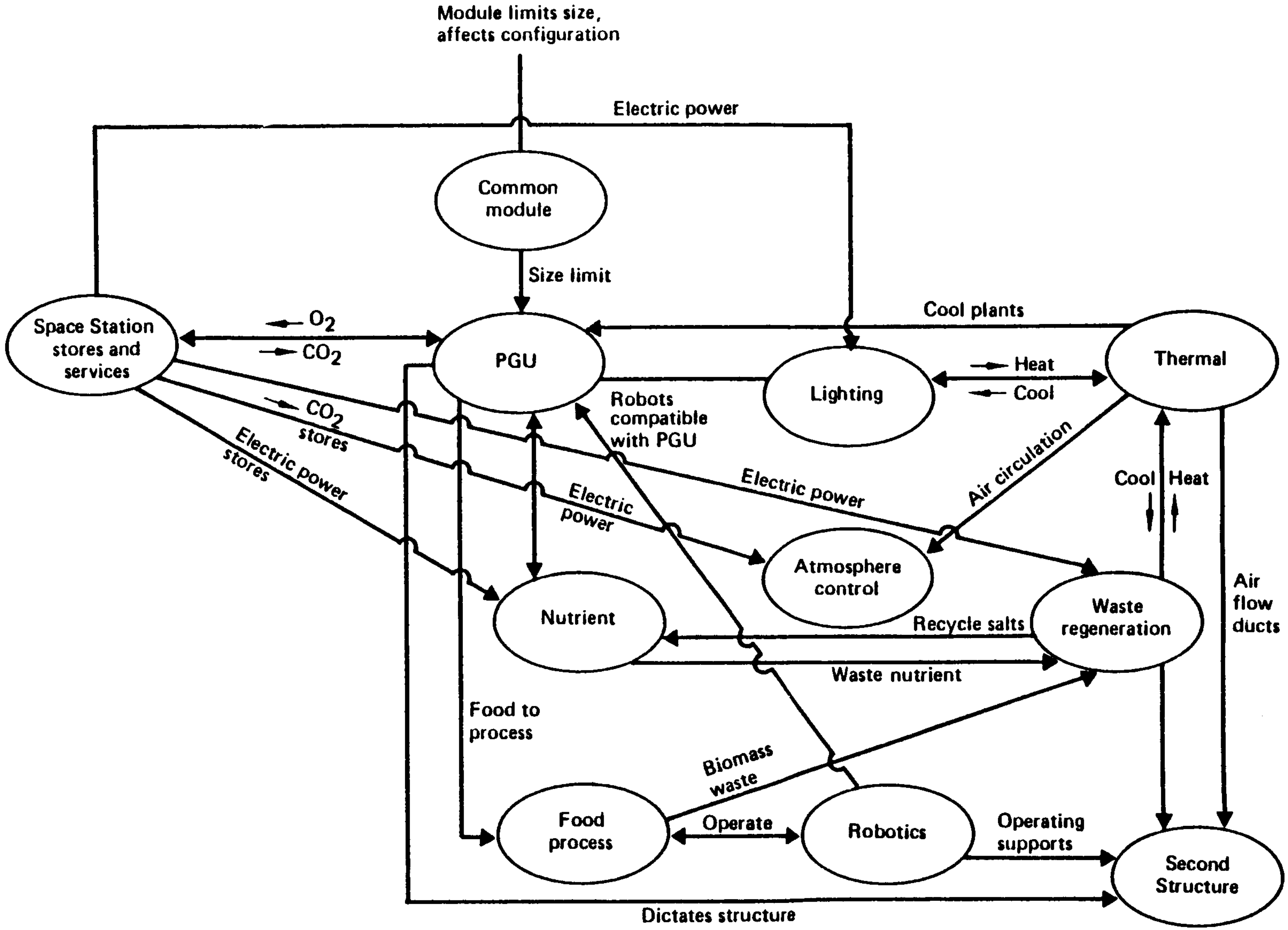


Figure 4.3-1. Preliminary Design Integration Flow

C-2

Several sources of artificial light to supplement collected solar rays are possible.

a. Direct fluorescent.
b. Xenon lamps.
c. HID lamps (High-pressure sodium).

Xenon and high-pressure sodium lamps are high-temperature, concentrated light sources and are considered in conjunction with a fiber optic light pipe distribution system. Xenon lamps require excessive power compared to fluorescent or high-pressure sodium lamps. Fluorescent and high-pressure sodium lamps require approximately the same net power for equal plant illumination. The fiber optic light pipe and focusing lens array required for high-pressure sodium lamps weigh much more than fluorescent luminaries and represent a greater development risk. collected solar rays supplemented by direct fluorescent lighting is the preferred lighting system for the CELSS plant growth illumination preliminary design.

4.3.2 Thermal Control Integration

PGU thermal control is critical to normal plant growth. Total heat loads from plant growth lighting are as follows:

a. Direct fluorescent lighting, 31,500 Btu/h from luminaries and ballasts and 8200 Btu/h from light energy on plants.
b. Collected solar ray/fiber optic distribution, 19,700 Btu/h from luminaries and 62,300 Btu/h from light energy on plants. Therefore, collected solar rays (natural light) sizes PGU thermal control.

CELSS PGU thermal control must be compatible with plants. Cooling jackets may work with luminaries, but are not feasible with growing plants. An atmospheric heat transfer method is feasible. Moving air past the plants by convection is not possible in microgravity but fans can maintain air motion to move heat away from plants. Forced cool air flow is selected as the preferred thermal control system for CELSS PGUs.

5.0 PARAMETER ESTIMATES

5.1 COST ESTIMATING PROCEDURE

The objective of the cost analysis was to provide a credible cost estimate for outfitting a CELSS module. The cost estimate was based on ground rules and assumptions developed in conjunction with the engineering staff as the study progressed. Several iterations were used to aid optimizing preliminary design. Cost model summaries, shown in table 5.1-1, identify total CELSS module cost of $677.8 million, ready for launch. This cost consists of (A) engineering costs of $176 million, (B) manufacturing costs of $579.8 million, and (C) support costs of $98 million.

This cost compares favorably with the estimated costs for other Space Station modules as shown in figure 5.1-1. (Note: the costs in fig. 5.1-1 are adjusted to reflect CELSS module construction in 1990 instead of 2000.)

The two primary tools used to estimate the hardware acquisition costs for the CELSS study were the Boeing parametric cost model (PCM) and the RCA developed parametric cost model (PRICE H). Since PCM is structured to represent the Boeing Aerospace Company costs and procedures it was used to integrate the acquisition cost estimate for plant growth and to generate most subsystem component costs.

PCM develops costs from hardware physical descriptions and program constraints. This model allows inclusion of costs generated by other methods. These throughput costs are handled within the PCM logic the same as PCM-generated costs. This process guarantees the proper impact on support costs (e.g., system engineering, ground test, program management, etc.). This model permits Boeing to use acquisition cost estimates from the best available source data.

Figure 5.1-2 illustrates the source, type, and level of information that can be handled by the Boeing integrated computerized system. As depicted in the illustration, the scope of study was defined by NASA and amplified by Boeing to establish the overall design, test, and fabrication philosophy required to successfully implement plant growth in space.

Table 5.1-1. CELSS–Laboratory Module Plant Growth–Base Input File: CELSS

HARDWARE SUBSYSTEM ($M):

ENGINEERING ($M)	ENGINEERING ($M) BOEING	SUBCONTR	GFE/GFP	TOTAL	
1 ROBOT	11.801	24.600	0.0	36.401	A
2 PLANT GROWTH NUTRIENT SUPPLY	2.697	5.163	0.0	7.861	A
3 SUPER CRITICAL H2O OXIDIZER	8.691	32.210	0.0	40.901	A
4 PLANT GROWTH TRAY ASSY	0.208	2.172	0.0	2.380	A
5 CONDUCTED SUNLIGHT PLANT LIG	3.511	6.651	0.0	10.162	A
6 PLANT LIGHTING SYS-FLUORESCE	2.237	2.212	0.0	4.449	A
7 HARVESTER	7.334	9.684	0.0	17.018	A
9 SEEDER	3.782	0.0	0.0	3.782	A
10 ATMOSPHERE CONTROL SYS	0.235	3.728	0.0	3.963	A
11 THERMAL CONTROL SYSTEM	8.110	3.811	0.0	11.921	A
12 POINTING & TRACKING SYS	2.209	35.000	0.0	37.209	A
ENGINEERING ($M)	50.815	125.232	0.0	176.047	

MANUFACTURING ($M)	MANUFACTURING ($M) BOEING	SUBCONTR	GFE/GFP	TOTAL	
1 ROBOT	41.019	28.977	0.0	69.996	B
2 PLANT GROWTH NUTRIENT SUPPLY	36.452	26.023	0.0	62.476	B
3 SUPER CRITICAL H2O OXIDIZER	8.597	14.198	0.0	22.795	B
4 PLANT GROWTH TRAY ASSY	8.788	8.171	0.0	16.959	B
5 CONDUCTED SUNLIGHT PLANT LIG	6.230	30.444	0.0	36.674	B
6 PLANT LIGHTING SYS-FLUORESCE	0.126	0.594	0.0	0.720	B
7 HARVESTER	18.690	6.763	0.0	25.453	B
8 LABORATORY MODULE	31.723	41.531	0.0	73.254	B
9 SEEDER	10.488	0.0	0.0	10.488	B
10 ATMOSPHERE CONTROL SYS	1.386	0.944	0.0	2.329	B
11 THERMAL CONTROL SYSTEM	10.782	1.927	0.0	12.709	B
12 POINTING & TRACKING SYS	0.0	7.000	0.0	7.000	B
MANUFACTURING SUBTOTAL ($M)	174.281	166.572	0.0	340.852	B
*HARDWARE FINAL ASSY & C/O	45.906	0.0	0.0	45.906	B
FLYAWAY COST ($M)	220.187	166.572	0.0	386.758	B
SPARES	8.714	8.329	0.0	17.043	B
MANUFACTURING ($M)	228.901	174.900	0.0	403.801	
HARDWARE ENGR & MFG TOTAL ($M)	279.716	300.132	0.0	579.847	

Table 5.1-1. CELSS—Laboratory Module Plant Growth—Base Input File: CELSS

	ENGR	MFG	TOTAL
HARDWARE TOTALS (FROM ABOVE) ($M)	176.047	403.801	579.847
SUPPORT COST ($M):	ENGR	MFG	TOTAL
SYSTEM ENGINEERING & INTEGRATION	9.491	-	9.491
SOFTWARE ENGINEERING	8.025	-	8.025
SYSTEMS GROUND TEST CONDUCT	18.003	-	18.003
SYSTEMS FLIGHT TEST CONDUCT	0.0	-	0.0
PECULIAR SUPPORT EQUIPMENT	4.235	5.316	9.551
TOOLING & SPECIAL TEST EQUIPMENT	-	33.156	33.156
LIAISON ENGINEERING	12.654	-	12.654
DATA	7.079	-	7.079
PROGRAM MANAGEMENT	0.0	0.0	0.0
SUPPORT EFFORT TOTAL ($M)	59.488	38.472	97.960
TOTAL ESTIMATE ($M)	235.534	442.273	677.807

C

D

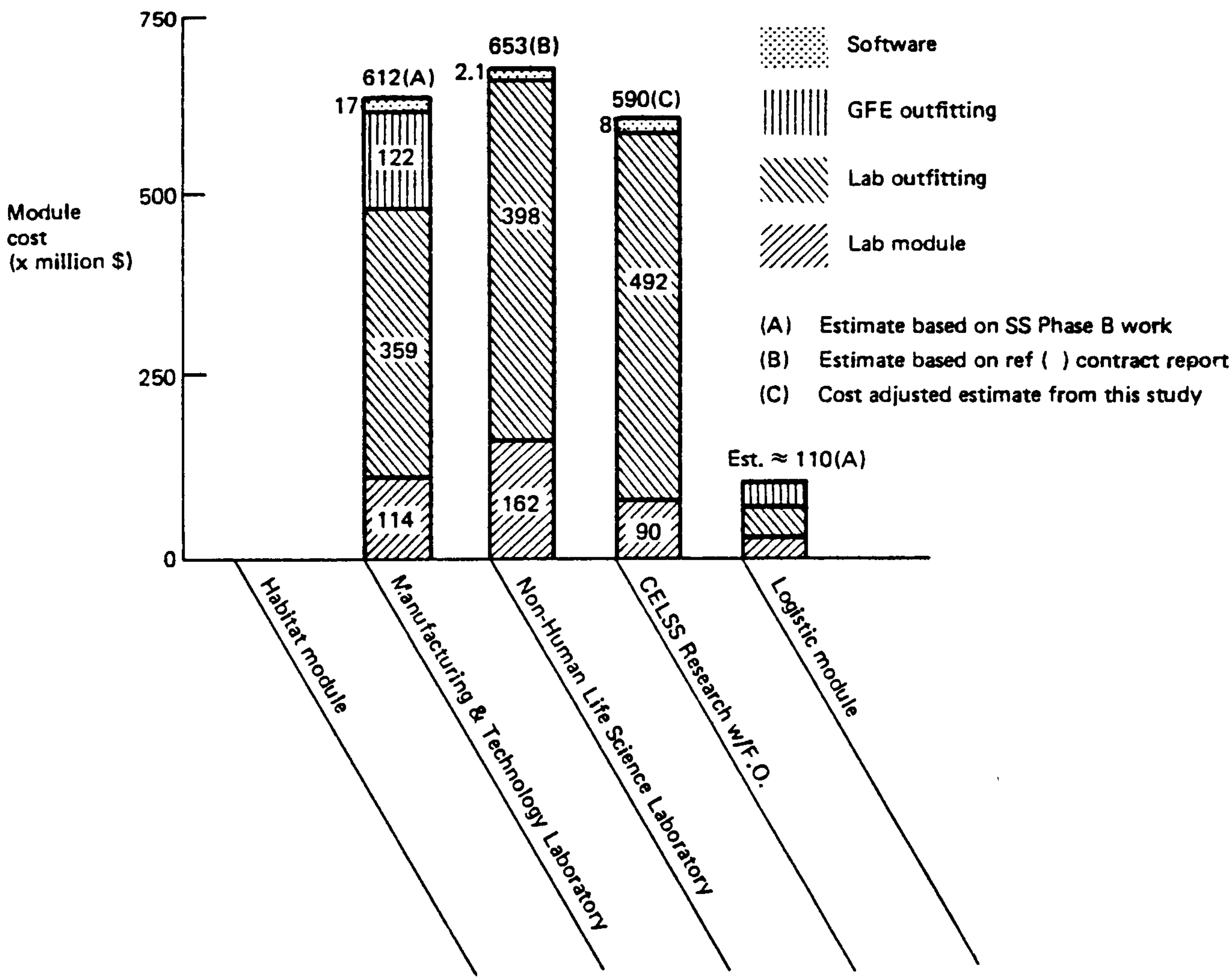


Figure 5.1-1. Space Station Module Cost Comparison

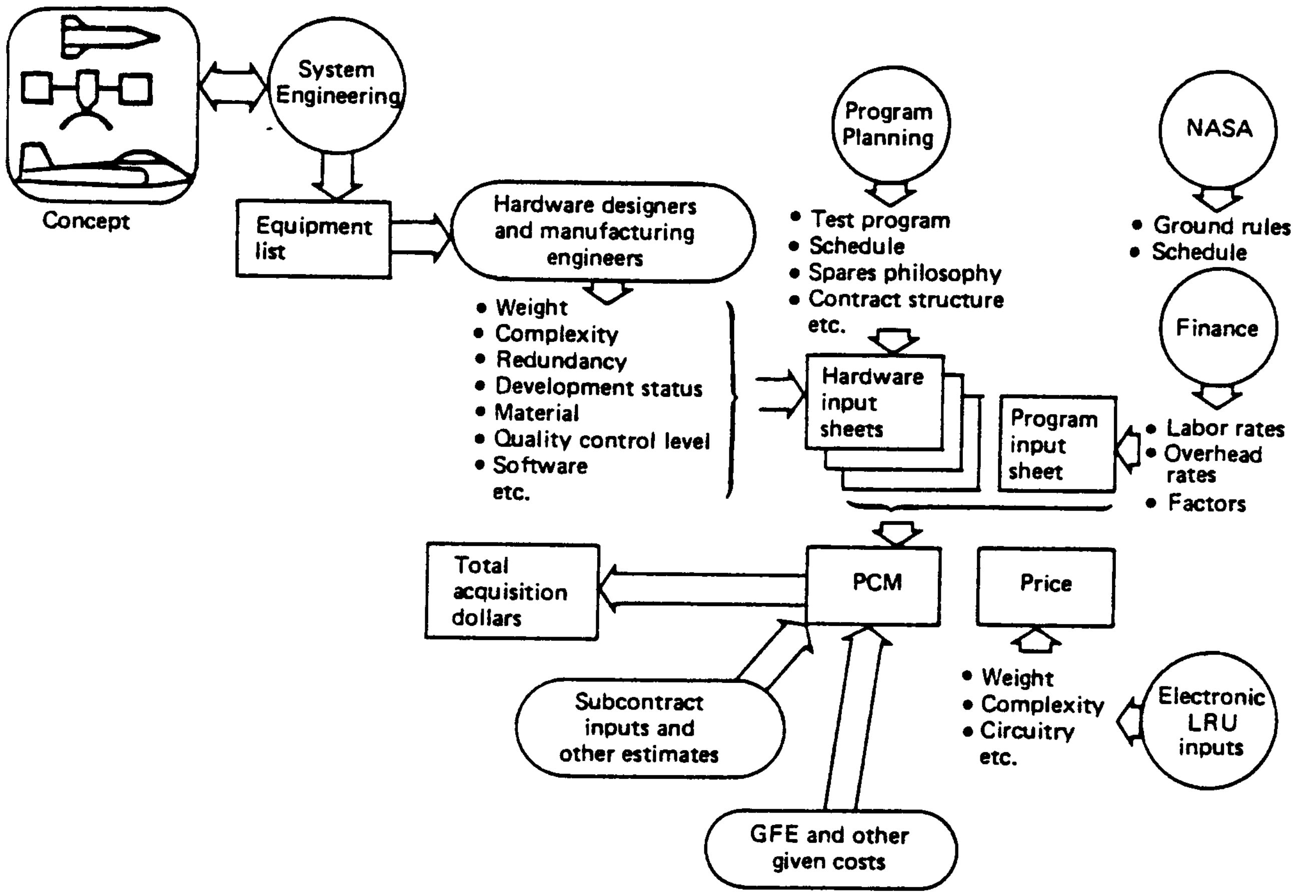


Figure 5.1-2. Costing Information Flow Diagram

These data, along with financial information relative to labor, support, and overhead rates comprise the program constraints within which the models work.

Figure 5.1-3 illustrates the data flow necessary to develop component hardware estimates. Engineering and manufacturing functionally describe the components that make up the system. Each component description includes weight, hardware type, complexity, quantity, learning curve, and manufacturing schedule. This hardware information, in conjunction with the programmatic data described above, are processed by PCM to generate the cost estimate.

PRICE H was used to generate hardware acquisition cost estimates for sensing devices, optics, and electronic hardware. PRICE H inputs are program constraints and hardware physical descriptions. The estimates generated by PRICE H were then throughput into PCM.

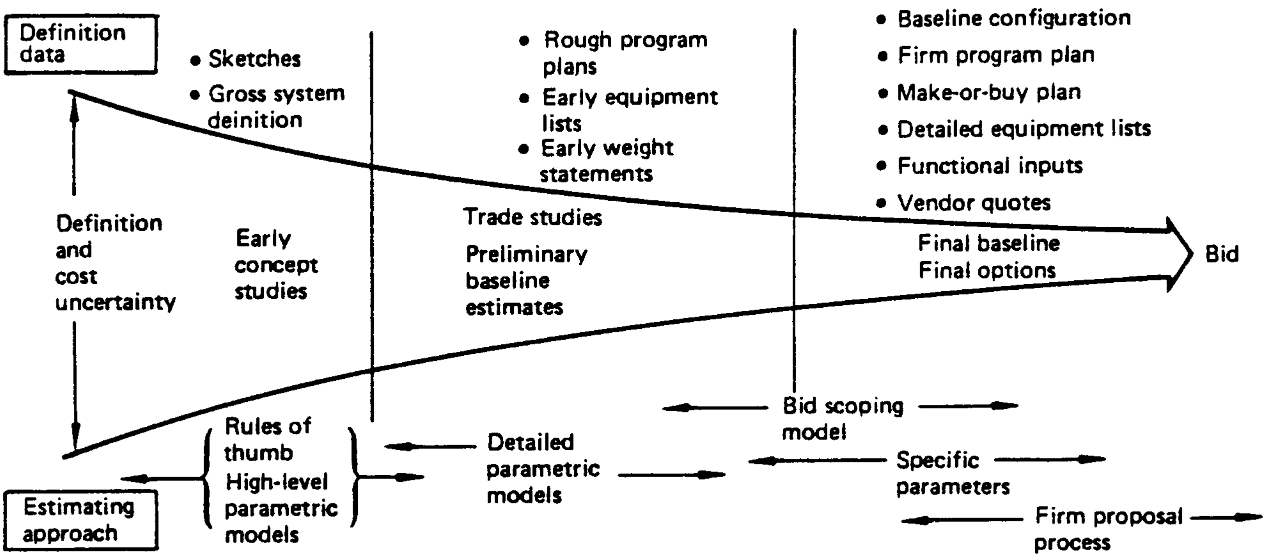


Figure 5.1-3. Boeing Aerospace Co. Cost Estimating Approach Flowchart

The costs estimated by PCM/PRICE H are all traceable to standardized input forms, with the information on the forms representing the engineering, manufacturing, and planning decisions that defined the estimate. Therefore, configuration control of the estimate was maintained throughout the estimating process.

The accuracy of this parametric approach is a function of (1) program and hardware definition, (2) the depth of analysis that translated this definition into cost model inputs, (3) the ability of the cost models to be sensitive to cost-driving conditions, and (4) the inherent accuracy of the models.

More specifically, these considerations translate into–

a. Quality of inputs.
b. Capability to handle NASA program conditions.
c. Inherent model accuracy.

Goodness of inputs is a function of hardware definition, program functionals, and estimator's capability to express the system in terms of model inputs. As the CELSS system definition evolved, considerable design detail yielded good hardware definition. PCM/PRICE is designed to accept increasing amounts of detail as the design evolves; the evolution results in more accurate estimates. Further, the technical and estimating

staff assigned to CELSS study have sufficient experience with the models to ensure successful interpretation of design concepts into model inputs.

The ability to handle real program conditions is enhanced by using PCM to integrate the total acquisition estimate. PCM is structured to be sensitive to varying design approaches, internal organization structures, and subcontracting philosophy. Inputs to the model are sensitive to design complexities, the use of off-the-shelf designs, development status, etc. To summarize, inputs to PCM are those that have been proven to directly relate to cost and customer reporting requirements.

Inherent model accuracy differs between PCM and the PRICE model. PCM estimating relationships are based on statistical correlation to Boeing history as contained in its standardized, company-wide data bank. These estimating relationships have been in continuous development since 1972 and are specifically designed for aerospace systems. Variance analysis has shown accuracy to within 23% when tested against known costs for mechanical, electrical, electromechanical, and propulsion hardware.

Estimating relationships in the PRICE models are proprietary to RCA and are not available to direct verification. However, the PRICE H model can be, and has been, calibrated to the Boeing aerospace environment using actual Boeing cost history and physical characteristics of the hardware.

5.1.1 Cost Parametric Ground Rules and Assumptions for CELSS

a. The estimate is in constant 1985 dollars.
b. 1985 full-scale development wrap rates for the Inertial Upper Stage program were used.
c. Customer-requested changes are not included in the cost estimates.
d. Program management has not been discretely estimated.
e. Spares were estimated to be 5% of hardware costs for Boeing and subcontract.
f. The schedule was assumed to be nominal.
g. Sets of peculiar support equipment: one.
h. Developmental shop hours were estimated to be 25% of total Boeing engineering hours.

i. Quality control hours were estimated to be 15% of total Boeing-furnished labor hours.
j. The estimate assumes high reliability requirements in a very corrosive environment.
k. It is assumed Space Station electrical power would be used to satisfy CELSS requirements.
l. Common module nonrecurring design costs are not included in the estimate.
m. A rough-order-of-magnitude (ROM) manufacturing cost to build one common module is included.
n. The ROM weight for the solar ray collector pointing system was estimated to be 500 lb.
o. Using rules of thumb, the cost to build the solar ray collector pointing system was estimated to be $7 million.
p. Again using rules of thumb, the nonrecurring design cost for the instrument pointing system was estimated to be $35 million.
q. Material sectors used reflect the use of corrosive resistant steel (CRES) for most hardware items.
r. Ninety percent learning curve was assumed on high quantity items only.
s. Estimate does not include fee.
t. Modification costs to the common module structure were not priced.

5.2 WEIGHT ESTIMATING PROCEDURE

Weight estimating methodology employed in developing the CELSS weight statement used preliminary design component weight estimating techniques. These techniques require a wide range of input parameters, including volume/density estimates, specifically calculated temperatures, pressure, and heat loads. Weight estimate summary is shown in figure 6.2-4.

Two basic assumptions apply to the CELSS weight analysis: (1) the source of the CELSS electrical power is the Space Station, and (2) the external portion of the conducted sunlight system (i.e., collector mirror, transmitter, etc.) is not included in the CELSS module weight statement.

CELSS is separated into six functional elements for weight estimating purposes. These functional areas are defined as follows:

a. Basic Capsule-Weight is derived from Space Station common module by removing systems not pertinent to CELSS. Aluminum is the principal structural material.

b. Plant Growth Units-Weight estimates for the PGUs, which include the growth trays, nutrient supply system, and lighting system, were based on preliminary sketches, schematics, and equipment lists. The baseline lighting system was considered to be conducted sunlight augmented with fluorescent lamps. Calculations used weights of existing hardware (valves, pumps, fluorescent bulbs, ballasts, and fiber optics) wherever possible.

c. Harvester-The harvester encloses a volume of approximately 1.3 m^3. Components were defined from a preliminary design equipment list and a density factor applied to each part.

d. Super Critical Water Oxidizer-Major components were defined and sized, including the air compressor. Sludge pumps and heat exchangers are the major weight parts.

e. Robot-The CELSS robot consists of a harvester unit and a planter. The units can move up and down along a pedestal connecting the tracks and rotate 360 deg about the pedestal. Major assumptions in weighing the robot were (1) there are no high-speed requirements for the motors, (2) there are no heavy-weight requirements because of zero gravity, and (3) there are six degrees of freedom for the harvester unit arm. The weight statement reflects aluminum structures for the tracks and mobile units.

f. Environmental Control-Heat dissipation requirements and the allowable temperature range for the plant growth environment were the significant factors in sizing, and therefore weighing, the environmental control system. The primary circulation unit was sized for approximately 40,000-Btu/h heat load dissipation and the moisture control system was sized for a moisture production rate of approximately 22.3 lb/h.

g. Weight Growth Allowance-To accommodate future weight increases due to design and manufacturing problems and development test results, a 15% weight growth allowance has been included in the CELSS weight statement.

6.0 SENSITIVITY ANALYSIS

Sensitivity analyses evaluated effects of each system on the CELSS module. Parametric values formed the basis for evaluation. Primary evaluations were conducted on mass and cost. Additional evaluations were conducted on selected systems for electrical power and volume. These analyses provide a means of judging the relative and actual impact of each system on the CELSS module.

These analyses indicate that electrical power and volume will drive technical design. These resources are most limited on the operational Space Station. Cost will also drive design by limiting design options to mitigate constraints of power and volume. Mass is a relatively minor impact on the operational CELSS module. Mass penalty is a one-time launch cost for the module. Consumable costs are not directly addressed in this study; however, the nature of the CELSS system to recycle materials should keep this cost within reasonable levels. A key resupply assumption is that an adequate CELSS waste recycling system is operational.

6.1 SENSITIVITY ANALYSIS APPROACH

Plant illumination system comparison is the basis for this sensitivity analysis. Plant illumination essentially determines edible biomass production. All other CELSS systems respond either directly to illumination (thermal, atmosphere control) or indirectly through biomass produced per day (robot, harvester, waste regeneration, etc.). Plant illumination levels are set to 750 micromole/m^2/s. Plant lighting systems are designed to provide this level during Space Station light-side operations. Dark-side plant light levels are set to 75 micromole/m^2/s for both artificial lighting systems. A system with only solar light produces range of 750 to 1000 micromole/m^2/s illumination level. An adjustment factor based on biomass production is used to equalize the parameters for solar-only and solar-plus-artificial lighting systems (sec. 6.3). Sensitivity analyses use the parametric values generated during the preliminary design and weighting/costing study tasks. These values are compiled to evaluate four questions.

a. What are power, mass, volume, and cost parametrics for each lighting option? (sec. 6.2)

b. How do power, mass, volume, and cost parameters compare between lighting configurations? (sec. 6.3)

c. What is CELSS power demand at any moment based on system activity? (sec. 6.4)

d. What are the parametric effects of mixing crop species to provide a balanced diet with greater variety? (sec. 6.5)

Analyses are discussed in subsequent subsections for each question. Conclusions and data developed are engineering estimates because the Space Station current early developmental stage precludes precise CELSS equipment parametric values.

Comparing systems of dissimilar design, but similar purpose, requires that a consistent approach be used in calculating parametrics.

a. Volume: Internal CELSS module equipment volumes are used in system comparisons. Internal module volume provides the plant growth space. Plant growth volume influences biomass production. Internal module equipment volumes impact the growth space. Externally mounted equipment, such as insulation blankets and solar ray collectors, do not reduce potential growth space. This study's primary interest is biomass production, which can only be accomplished internally.

b. Mass: All CELSS equipment mass are considered in comparisons. All equipment must be lifted into orbit; launch costs are related to equipment mass. CELSS launch cost must consider the mass of all related equipment. Once in orbit, equipment mass has little impact or CELSS operation. Additional Space Station reboost fuel mass will be needed; however, the amount is insignificant to overall station fuel needs.

c. Electrical Power: All electrical power demands are included in comparisons. Power usage by any CELSS system are chargeable to the CELSS power allocation budget from the Space Station. CELSS system loads must be balanced to stay within budget. Orbital light/dark cycles affect power allocation. Direct photovoltaic conversion on light-side orbit will permit target power allocations. Dark-side fuel cell operations will limit power allocation. CELSS system activities are geared to

this cycle. Most power-consuming activity occurs during light-side phase. Only critical plant support and illumination systems are operated during dark-side cycle. Normal equipment operating power values are used to avoid skewing comparisons by considering transient peak values.

d. Cost: Total cost for all equipment is used in comparisons. These costs are the summation of engineering and development costs, hardware costs, assembly costs, and support service costs. Launch costs are not included in values as they are a one-time, system-wide cost. Operational costs and resupply costs are outside the scope of this study.

Four CELSS systems were evaluated for sensitivity analysis.

a. Solar ray collector only using fiber optic cables to pipe light to plants.

b. Solar ray collector with fluorescent light for low-level, dark-side illumination. fluorescent lamps are mounted directly over the plants.

c. Solar ray collector with HID lamps for dark-side, low-level illumination. Fiber optics pipe light to plants from HID source.

d. Artificial light only from HID source directly over plants. Direct-illuminating fluorescent lights are used as a baseline for systems comparison.

6.2 SYSTEMS PARAMETRICS ANALYSIS

Each system parameter is presented in tables 6.2-1 through 6.2-4. Bar chart plots derived from data in tables for each system parameter are presented in figures 6.2-1 through 6.2-4. Evaluating these data indicates that electrical power consumption (table 6.2-1) can range from 6.8 kW to 87.8 kW peak demand. Major power consumption depends on the system employed. Artificial lighting operated at high intensity consumes 83.4% of CELSS module power. Even low-intensity artificial lighting consumes about 62% module peak power.

ELECTRICAL POWER DEMAND (WATTS) (MAJOR SYSTEMS UNADJUSTED)		ARTIFICIAL ONLY	SOLAR ONLY	SOLAR + FLOURESCENTS	SOLAR + FO HID
PLANT GROWTH UNIT	TRAY SUPPORT SYSTEM	0.0	0.0	0.0	0.0
	SEED PLANTER	0.0	0.0	0.0	0.0
	SEED CARTRIDGES	0.0	0.0	0.0	0.0
	TOTAL=	0.0	0.0	0.0	0.0
LIGHTING SYSTEM	LOW LEVEL ARTIFICIAL LIGHT	0.0	0.0	10560.0	10320.0
	ART INDIRECT LIGHTING	69660.0	0.0	0.0	0.0
	SOLAR F.O. LIGHTING (INSIDE	NA	0.0	0.0	0.0
	F.O. CABLE (SOLAR INSIDE	NA	0.0	0.0	0.0
	BALLASTS	3483.0	0.0	1056.0	1032.0
	PROCESS CONTROLLER	8.0	8.0	8.0	8.0
	EXTERNAL SOLAR COLLECTOR	0.0	375.0	375.0	375.0
	EXTERNAL F.O. CABLE	0.0	0.0	0.0	0.0
	F.O. inside cable	0.0	0.0	0.0	0.0
	TOTAL=	73151.0	33.0	11999.0	11735.0
THERMAL CONTROL SYSTEM					
	RADIATORS	0.0	0.0	0.0	0.0
	PUMPS/FANS/ACCUMULATORS	6886.0	2263.0	2400.0	2400.0
	HEAT EXCHANGERS	0.0	0.0	0.0	0.0
	INSULATION	0.0	0.0	0.0	0.0
	TOTAL=	6886.0	2263.0	2400.0	2400.0
NUTRIENT SUPPLY SYSTEM	NUTRIENT PIPING	360.0	360.0	360.0	360.0
	NUTRIENT REGENERATION	1820.0	1820.0	1820.0	1820.0
	NUTRIENT REPLENISHMENT	0.0	0.0	0.0	0.0
	TOTAL=	2180.0	2180.0	2180.0	2180.0
ATMOSPHERE CONTROL SYSTEM					
	CONTAMINANT CONTROL	202.0	202.0	202.0	202.0
	CONSTITUENT CONTROL	457.0	457.0	457.0	457.0
	TOTAL=	659.0	659.0	659.0	659.0
WATE REGENERATION SYSTEM					
	SUPER CRITICAL WTR OXI	373.0	373.0	373.0	373.0
	SALT SEPARATOR	0.0	0.0	0.0	0.0
	HEAT EXCHANGER	0.0	0.0	0.0	0.0
	TANKAGE	0.0	0.0	0.0	0.0
	TOTAL=	373.0	373.0	373.0	373.0
MODULE STRUCTURE					
	PRIMARY STURCTURE	0.0	0.0	0.0	0.0
	COMMUNICATIONS	0.0	0.0	0.0	0.0
	ELECTRICAL SYSTEM	3784.0	307.0	970.0	970.0
	DATA HANDLING	315.0	315.0	315.0	315.0
	FINAL ASSEMBLY	0.0	0.0	0.0	0.0
	SPARES	0.0	0.0	0.0	0.0
	TOTAL=	4099.0	622.0	1285.0	1285.0
FOOD PROCESSING	HARVESTER	0.0	0.0	0.0	0.0
	PROCESSOR	0.0	0.0	0.0	0.0
	STORAGE	0.0	0.0	0.0	0.0
	WASTE PROCESSOR	0.0	0.0	0.0	0.0
	INEDIBLE MASS RECOVERY	0.0	0.0	0.0	0.0
	TOTAL=	0.0	0.0	0.0	0.0
ROBOTICS	ROBOTIC GARDENER	193.0	193.0	193.0	193.0
	ROBOT TOOLS	140.0	140.0	140.0	140.0
	SUPPORT STRUCTURE	0.0	0.0	0.0	0.0
	TOTAL=	333.0	333.0	333.0	333.0
SYSTEM TOTAL=	SYSTEM TOTALS=	87681.0	6813.0	19229.0	18965.0
	PLANT GROWTH UNIT	0.0%	0.0%	0.0%	0.0%
	LIGHTING	83.4%	5.6%	62.4%	61.9%
	THERMAL CONTROL	7.9%	33.2%	12.5%	12.7%
	NUTRIENT SUPPLY	2.5%	32.0%	11.3%	11.5%
	ATMOSPHERE CONTROL	0.8%	9.7%	3.4%	3.5%
	WASTE REGERNERATIO	0.4%	5.5%	1.9%	2.0%
	MODULE STRUCTURE	4.7%	9.1%	6.7%	6.8%
	FOOD PROCESSING	0.0%	0.0%	0.0%	0.0%
	ROBOTICS	0.4%	4.9%	1.7%	1.8%
		100.0%	100.0%	100.0%	100.0%

Table 6.2-1. Peak Electrical Power Demand Comparison

VOLUME (M3)		SOLAR ONLY	SOLAR + FLOURESCENTS	SOLAR + FO HID
PLANT GROWTH UNIT	TRAY SUPPORT SYSTEM	41.2	41.2	41.2
	SEED PLANTER	0.3	0.3	0.3
	SEED CARTRIDGES	0.3	0.3	0.3
	TOTAL=	41.8	41.8	41.8
LIGHTING	LOW LEVEL ARTIFICIAL LIGHT	0.0	6.1	2.8
	SOLAR F.O. LIGHTING (TERMINALS)	6.1	0.6	6.1
	F.O. CABLE (SOLAR INSIDE)	0.6	0.6	0.6
	BALLASTS	0.0	0.7	0.1
	PROCESS CONTROLLER	0.1	0.1	0.1
	EXTERNAL SOLAR COLLECTOR	0.0	0.0	0.0
	EXTERNAL F.O. CABLE	0.0	0.0	0.0
	HID F.O. CABLE (INSIDE)	0.0	0.0	0.6
	TOTAL=	6.8	8.1	10.3
THERMAL CONTROL SYSTEM				
	RADIATORS	0.0	0.0	0.0
	PUMPS/FANS/ACCUMULATORS	0.5	0.5	0.5
	HEAT EXCHANGERS	0.4	0.4	0.4
	INSULATION	0.0	0.0	0.0
	TOTAL=	0.9	0.9	0.9
NUTRIENT SUPPLY SYSTEM	NUTRIENT PIPING	0.5	0.5	0.5
	NUTRIENT REGENERATION	0.5	0.5	0.5
	NUTRIENT REPLENISHMENT	0.1	0.1	0.1
	TOTAL=	1.1	1.1	1.1
ATMOSPHERE CONTROL SYSTEM				
	CONTAMINANT CONTROL	2.4	2.4	2.4
	CONSTITUENT CONTROL	3.5	3.5	3.5
	TOTAL=	5.9	5.9	5.9
WASTE REGENERATION SYSTEM				
	SUPER CRITICAL WTR OXI	0.4	0.4	0.4
	SALT SEPARATOR	0.2	0.2	0.2
	HEAT EXCHANGER	0.1	0.1	0.1
	TANKAGE	0.5	0.5	0.5
	TOTAL=	1.2	1.2	1.2
MODULE STRUCTURE	PRIMARY STURCTURE	9.8	9.8	9.8
	COMMUNICATIONS	0.0	0.0	0.0
	ELECTRICAL SYSTEM	0.0	0.0	0.0
	DATA HANDLING	0.7	0.7	0.7
	FINAL ASSEMBLY	0.0	0.0	0.0
	SPARES	7.2	7.2	7.2
	TOTAL=	17.7	17.7	17.7
FOOD PROCESSING	HARVESTER	0.4	0.4	0.4
	PROCESSOR	0.3	0.3	0.3
	STORAGE	0.3	0.3	0.3
	WASTE PROCESSOR	0.1	0.1	0.1
	INEDIBLE MASS RECOVERY	0.2	0.2	0.2
	TOTAL=	1.3	1.3	1.3
ROBOTICS	ROBOTIC ARDENER	0.6	0.6	0.6
	ROBOT TOOLS	0.6	0.6	0.6
	SUPPORT STRUCTURE	0.2	0.2	0.2
	TOTAL=	1.4	1.4	1.4
SYSTEM TOTAL=	SYSTEM TOTALS=	78.1	79.4	81.6
	PLANT GROWTH UNIT	53.5%	52.6%	51.2%
	LIGHTING	8.7%	10.2%	12.6%
	THERMAL CONTROL	1.2%	1.1%	1.1%
	NUTRIENT SUPPLY	1.4%	1.4%	1.3%
	ATMOSPHERE CONTROL	7.6%	7.4%	7.2%
	WASTE REGERNERATION	1.5%	1.5%	1.5%
	MODULE STRUCTURE	22.7%	22.3%	21.7%
	FOOD PROCESSING	1.7%	1.6%	1.6%
	ROBOTICS	1.8%	1.8%	1.7%
		100.0%	100.0%	100.0%

Table 6.2-2. Volume Comparison

		ONLY	FLOURESCENTS	SOLAR + FO HID
PLANT GROWTH UNIT	TRAY SUPPORT SYSTEM	21.0	21.0	21.0
	SEED PLANTER	15.6	15.6	15.6
	SEED CARTRIDGES	1.9	1.9	1.9
	TOTAL=	38.5	38.5	38.5
LIGHTING	LOW LEVEL ARTIFICIAL LIGHT	0.0	5.7	0.0
	SOLAR F.O. SYS (INTERNAL)	50.6	50.6	50.6
	PROCESS CONTROLLER	0.3	0.3	0.3
	SOLAR F.O. SYS (EXTERNAL)	98.8	98.8	98.8
	HID F.O. SYSTEM	0.0	0.0	69.0
	TOTAL=	149.7	155.4	218.7
THERMAL CONTROL SYSTEM	TOTAL=	22.8	22.8	22.8
NUTRIENT SUPPLY	TOTAL=	76.1	76.1	76.1
ATMOSPHERE CONTROL SYSTEM	TOTAL=	6.9	6.9	6.9
WASTE REGENERATION SYSTEM	TOTAL=	69.2	69.2	69.2
MODULE STRUCTURE	PRIMARY STURCTURE	79.5	79.5	79.5
	INAL ASSEMBLY	49.8	49.8	49.8
	SPARES	18.5	18.5	18.5
	TOTAL=	147.8	147.8	147.8
FOOD PROCESSING	TOTAL=	45.7	45.7	45.7
ROBOTICS	TOTAL=	115.4	115.4	115.4
	SYSTEM TOTALS=	672.1	677.8	741.1
	PLANT GROWTH UNIT	5.7%	5.7%	5.2%
	LIGHTING	22.3%	22.9%	29.5%
	THERMAL CONTROL	3.4%	3.4%	3.1%
	NUTRIENT SUPPLY	11.3%	11.2%	10.3%
	ATMOSPHERE CONTROL	1.0%	1.0%	0.9%
	WASTE REGERNERATIO	10.3%	10.2%	9.3%
	MODULE STRUCTURE	22.0%	21.8%	19.9%
	FOOD PROCESSING	6.8%	6.7%	6.2%
	ROBOTICS	17.2%	17.0%	15.6%
		100.0%	100.0%	100.0%

Table 6.2-3. Cost Comparison by Illumination System

MASS (KG)		SOLAR ONLY	SOLAR + FLOURESCENTS	SOLAR + FO HID
PLANT GROWTH UNIT	TRAY SUPPORT SYSTEM	704.8	704.8	704.8
	SEED PLANTER	32.8	32.8	32.8
	SEED CARTRIDGES	257.0	257.0	257.0
	TOTAL=	94.6	994.6	994.6
LIGHTING	LOW LEVEL ARTIFICIAL LIGHT	0.0	980.0	1064.6
	SOLAR F.O. LIGHTING (TERMINALS)	1652.0	1652.0	1652.0
	F.O. CABLE (SOLAR INSIDE)		51.7	51.7
	BALLASTS	0.0	135.1	135.1
	PROCESS CONTROLLER	4.5	4.5	4.5
	EXTERNAL SOLAR COLLECTOR	2644.4	2644.4	2644.4
	EXTERNAL F.O. CABLE	595.1	595.1	595.1
	HID F.O. CABLE (INSIDE)	607.0		924.0
	TOTAL=	5503.0	6062.8	7071.4
THERMAL CONTROL SYSTEM	RADIATORS	655.4	655.4	655.4
	PUMPS/FANS/ACCUMULATORS	752.0	752.0	752.0
	HEAT EXCHANGERS	587.0	587.0	587.0
	INSULATION	112.0	112.0	112.0
	TOTAL=	2106.4	2106.4	2106.4
NUTRIENT SUPPLY SYSTEM	NUTRIENT PIPING	228.5	228.5	228.5
	NUTRIENT REGENERATION	303.0	303.0	303.0
	NUTRIENT REPLENISHMENT	348.4	348.4	348.4
	TOTAL=	879.9	879.9	879.9
ATMOSPHERE CONTROL SYSTEM	CONTAMINANT CONTROL	267.0	267.0	267.0
	CONSTITUENT CONTROL	424.0	424.0	424.0
	TOTAL=	691.0	691.0	691.0
WASTE REGENERATION SYSTEM	SUPER CRITICAL WTR OXI	64.8	64.8	64.8
	SALT SEPARATOR	59.0	59.0	59.0
	HEAT EXCHANGER	22.7	22.7	22.7
	TANKAGE	87.9	87.9	87.9
	TOTAL=	234.4	234.4	234.4
MODULE STRUCTURE	PRIMARY STURCTURE	6754.0	6754.0	6754.0
	COMMUNICATIONS	53.0	53.0	53.0
	ELECTRICAL SYSTEM	423.0	423.0	423.0
	DATA HANDLING	604.1	604.1	604.1
	FINAL ASSEMBLY	NA	NA	NA
	SPARES	1034.9	1034.9	1034.9
	TOTAL=	8869.0	8869.0	8869.0
FOOD PROCESSING	HARVESTER	117.9	117.9	1179
	PROCESSOR	147.0	147.0	147.0
	STORAGE	100.0	100.0	100.0
	WASTE PROCESSOR	100.2	100.2	100.2
	INEDIBLE MASS RECOVERY	NA	NA	NA
	TOTAL=	465.1	465.1	465.1
ROBOTICS	ROBOTIC GARDENER	6.5	63.5	63.5
	ROBOT TOOLS	46.2	46.2	46.2
	SUPPORT STRUCTURE	136.1	136.1	136.1
	TOTAL=	245.8	245.8	245.8
SYSTEM TOTAL=	SYSTEM TOTALS=	19989.2	20549.0	21557.6
	PLANT GROWTH UNIT	5.0%	4.8%	4.6%
	LIGHTING	27.5%	29.5%	32.8%
	THERMAL CONTROL	10.5%	10.3%	9.8%
	NUTRIENT SUPPLY	4.4%	4.3%	4.1%
	ATMOSPHERE CONTROL	3.5%	3.4%	3.2%
	WASTE REGERNERATION	1.2%	1.1%	1.1%
	MODULE STRUCTURE	44.4%	43.2%	41.1%
	FOOD PROCESSING	2.3%	2.3%	2.2%
	ROBOTICS	1.2%	1.2%	1.1%
		100.0%	100.0%	100.0%

Table 6.2-4. Mass Comparison

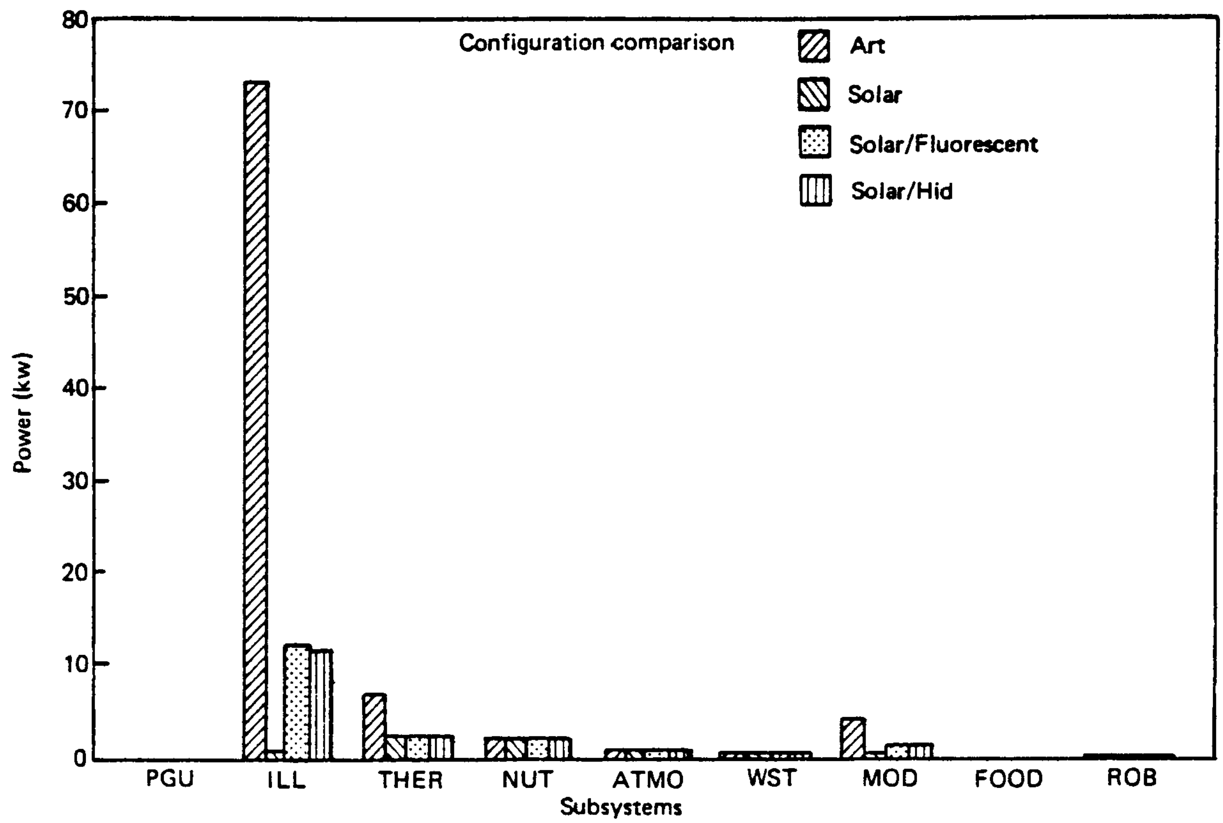


Figure 6.2-1. CELSS Electrical Power Configuration Comparison

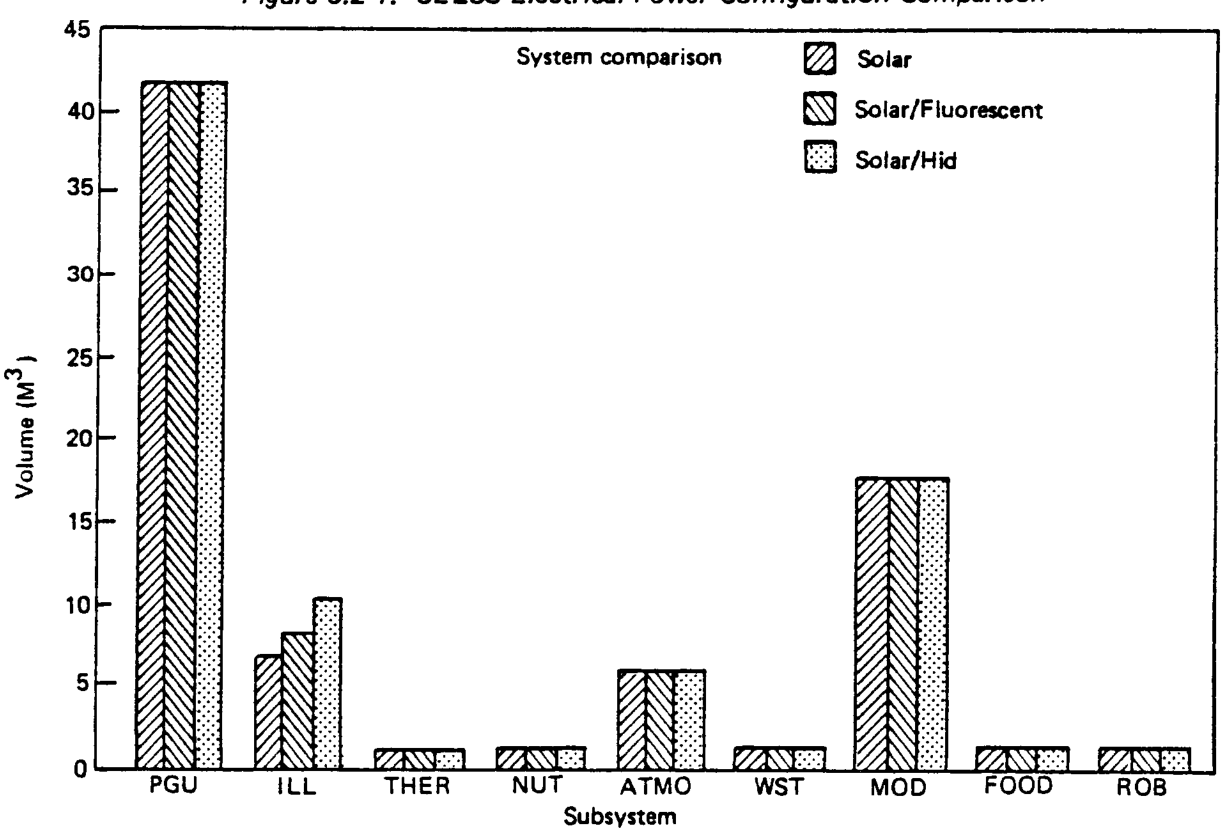


Figure 6.2-2. CELSS Volume Configuration Comparison

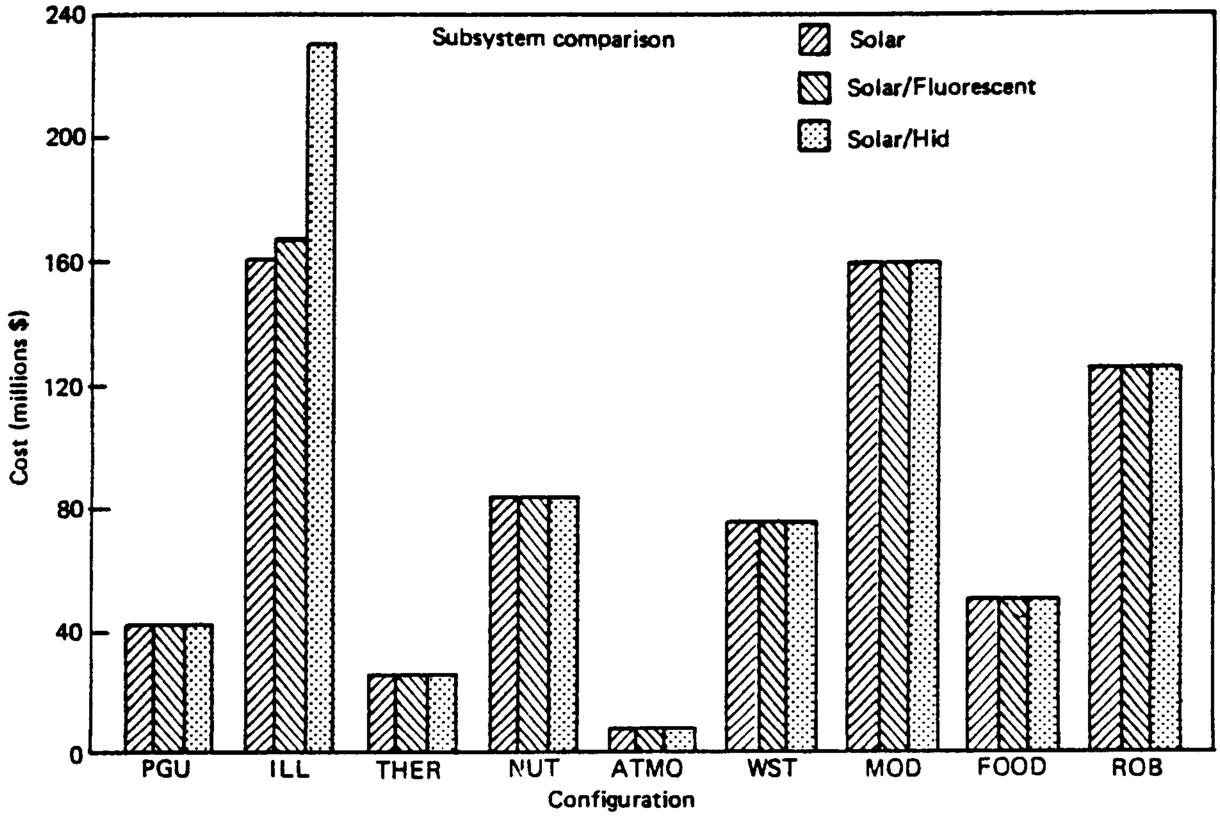


Figure 6.2-3. CELSS Cost Configuration Comparison

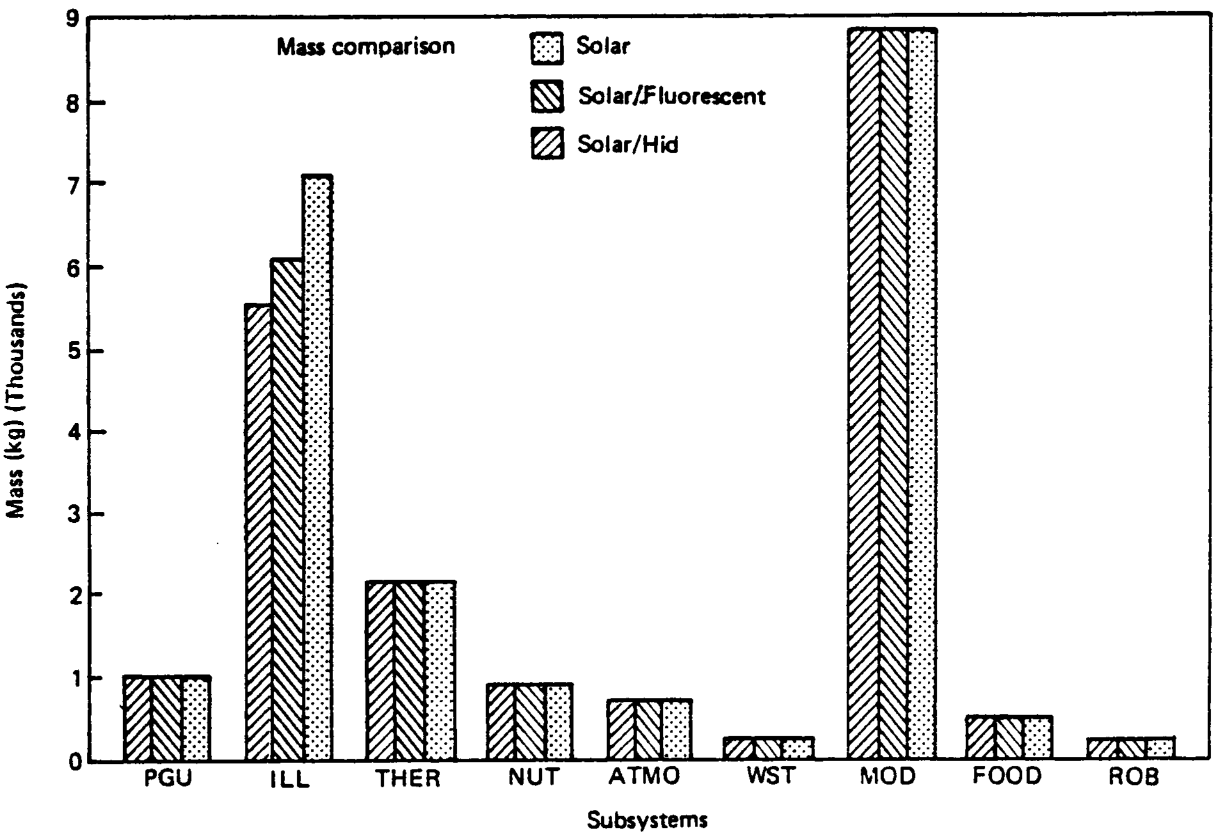


Figure 6.2-4. CELSS Mass Configuration Comparison

Equipment volume requirements (table 6.2-2) are about 80 m^3. This is slightly over one-half of a module for equipment. Additional space will be needed for maintenance and access. An additional 43% is allowed for these functions (1). This totals 114 m^3 for two crew members. PGUs consume the most volume, 53%. Slight variation in volume distribution occurs with differing lighting schemes.

Approximately $749 million (table 6.2-3) are required for the first two-person CELSS module. Additional modules will cost about $459 million.

Mass values (table 6.2-4) are within current shuttle 23 600 kg launch limits. total system mass averages 20 700 kg. Primary module structure, at 8869 kg, composes the largest mass portion, 43%. Illumination system averages 5900 kg, about 27%. Water weights are not included because plans are to use Space Station waste water for nutrient makeup.

6.3 ILLUMINATION SYSTEM COMPARISON

Lighting systems are the major differences in system designs. Each system optimizes some aspect of CELSS design. The solar ray collector using fiber optic light piping has low power consumption relative to other systems. This optimization creates conditions that can negate the improvements. For example, the solar ray collector will be shadowed for 30 min out of every 90 min. During the shadowed period, many plant species will shift from photosynthetic to a respiratory state. Transition back to the photosynthetic state can take a few too many minutes depending on species. This rapid cycling of metabolic state can adversely affect plant morphology and development. Less than continuous light decreases wheat edible biomass yield and can increase growth cycle.

Illumination intensity at the plant canopy forms the constant value to which each system is designed. All other CELSS systems are sized to support illumination system requirements. The full-intensity illumination level during light-side operations is 750 micromol/m^2/s. This level (1) Life Science Research Facility NAS8-35471, 1985 corresponds with full-intensity wheat lighting (ref). Dark-side orbital lighting is evaluated at full intensity (750 micromol/m^2/s), one-tenth intensity (75 micromol/m^2/s) and module ambient lighting (<1 micromol/m^2/s).

Light-side lighting is provided by a visible light solar ray collector (fig. 6.3-1). This collector connects with fiber optic cables that transmit the light to the plant growth areas. fiber optic terminal illuminators distribute the solar light to the plants at predetermined intensities. Each lighting system that uses a solar ray collector uses the same collector design. This reduces variability in comparing each lighting system.

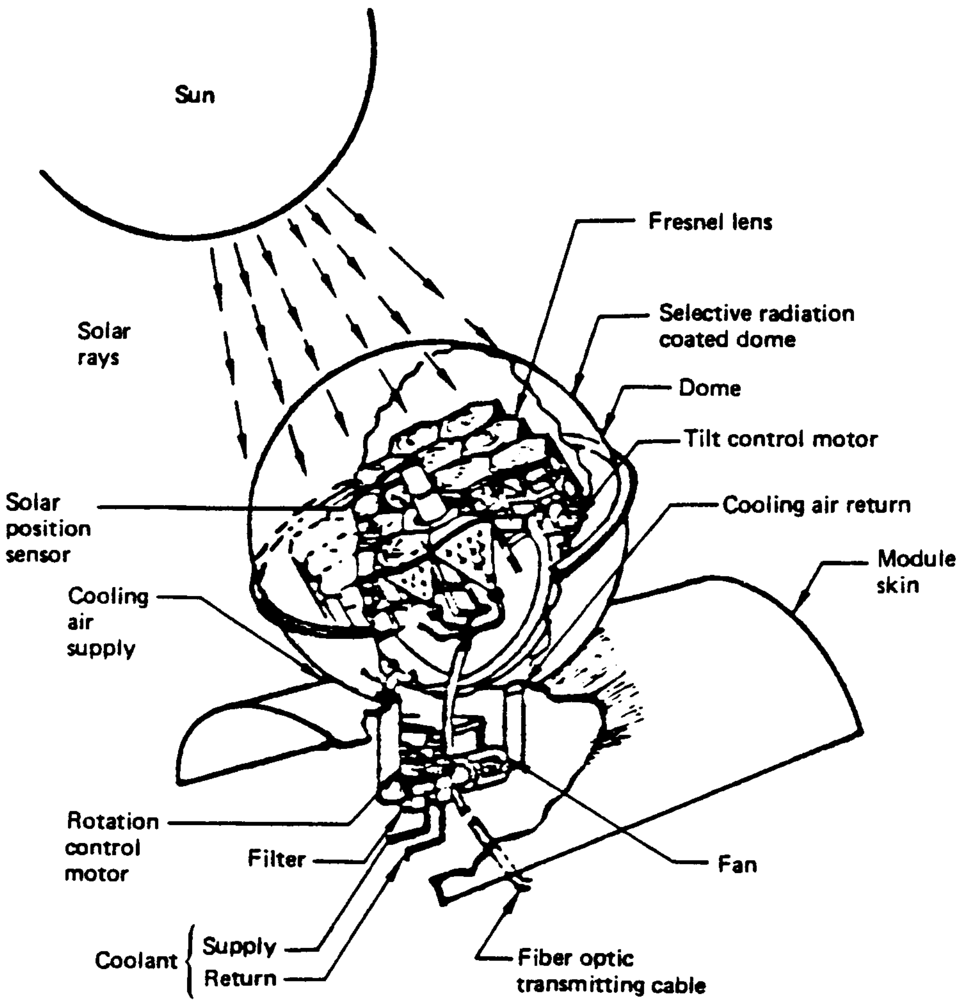


Figure 6.3-1. Fresnel Lens Lighting System

Dark-side illumination originates with electrically powered artificial light sources. These sources are either fluorescent or HID lamps. Electrical power is drawn from space Station fuel cells. No significant power sources are on the CELSS module.

Four illumination systems are initially considered in the preliminary design.

a. Artificial full-intensity illumination only.

b. Solar ray full-intensity illumination.

c. Solar ray full-intensity illumination plus fluorescent dark-side partial-intensity illumination.

d. Solar ray full-intensity illumination plus HID dark-side partial-intensity illumination using fiber optic cables to pipe the light.

Determining an optimum illumination system was the sensitivity analysis goal. An optimum system produces maximum edible biomass per unit of Space Station volume. Edible biomass produced per kilowatt consumed by CELSS module is considered in selecting the best illumination system. Illumination system power consumptions are compared in figure 6.3-2. A discussion of each system's electrical power demand follows.

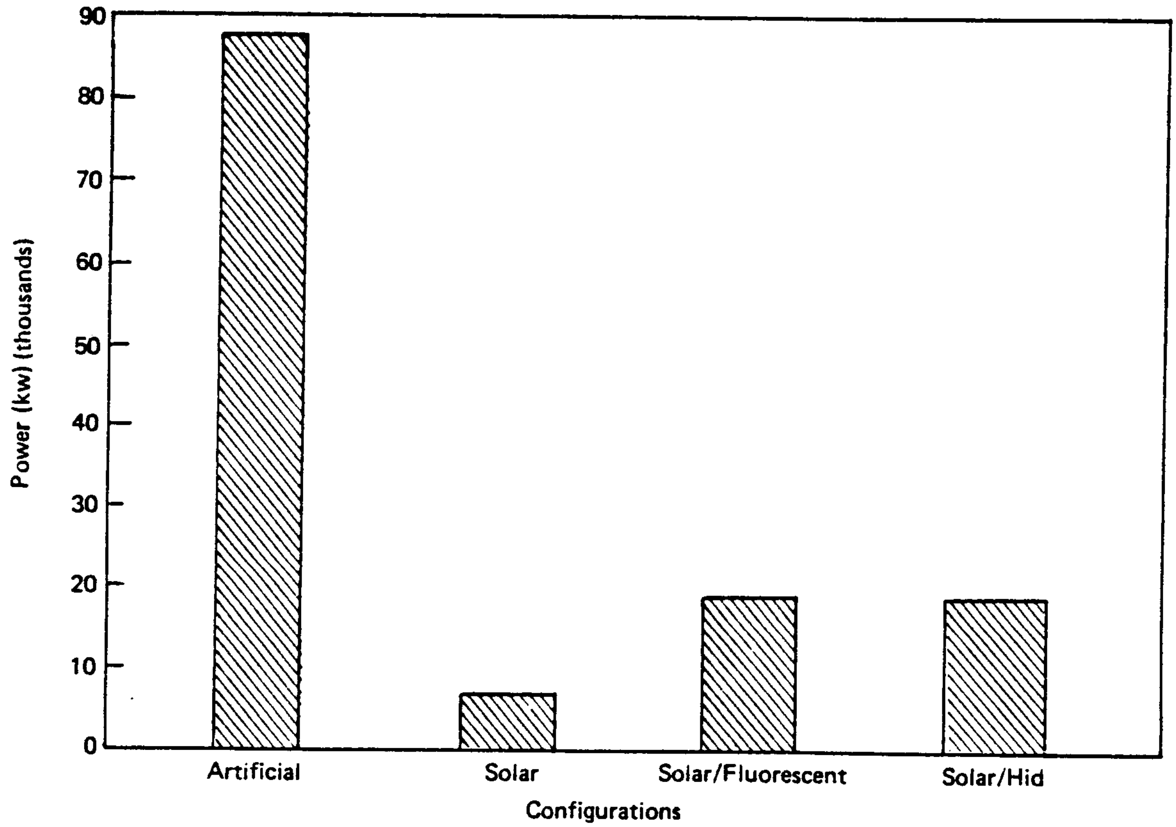


Figure 6.3-2. Illumination System Power Comparison

HID lamps produce light at high intensity that is routed to plants through fiber optic light pipes. This approach was selected to minimize subsystem volume and power requirements compared with direct fluorescent or direct HID illumination. Continuous artificial lighting subsystem power demand is 73 kW (table 6.2-1). Total CELSS power demand reaches 87.7-kW peak power when supporting systems are included. This significantly impacts thermal control requirements, driving it up to 6.9 kW. Just the

power loss from line drop and electrical connections approaches 4.1 kW. These latter two values alone nearly add up to the total power requirement for the next most power-intensive system, (solar plus fluorescent at 12 kW). With total Space Station power in 1999 predicted at 210 kW, the artificial-only lighting system would draw 44% of station power. This massive power demand essentially eliminates artificial lighting as the sole light source.

Alternative design uses a visible light solar ray collector (fig. 6.3-1) as the sole illumination source. These collectors are mounted on Space Station masts for optimum exposure to sunlight. Fiber optic cables carry the collected sunlight to the PGUs. Light is directed onto the plants by columniating fiber optic terminal illuminators. No plant illumination occurs during Space Station dark-side operations. Power requirements total 0.37 kW for the solar light collector subsystem. This power drives motors and sensors that maintain collector orientation to the Sun. The intense light level does require an extensive thermal and atmosphere control systems. These systems consume 2.3 kW and 0.7 kW, respectively. Overall CELSS system demand is 6.8-kW peak power (fig. 6.3-2). This uses 3.2% of Space Station power. A significant question arises about the effects on plant physiology and morphology caused by 16 dark/light cycles per day. Yields may be substantially lower and growth cycles greatly lengthened.

Hybrid lighting systems are proposed to resolve the plant growth questions associated with a solar-only system while avoiding the high energy requirements from a full-intensity system. Hybrid systems use solar collectors during light-side operations, then shift to low-intensity artificial lighting during dark-side operations. The low intensity maintains the plants in a photosynthetic state, provides phototrophic stimuli for orientation, and maintains a normal lighting cycle. Low intensity levels would equate to a cloud passing over a field, a condition plants are adapted to handle without adverse physiological or morphological effects. Crop yields probably are going to decrease under hybrid lighting when compared to continuous, full-intensity lighting. This results from decreased total photon flux per day because 33% of each day is at 10% full illumination.

Identical solar collection subsystems are used for both hybrid systems. This is the same collector used in the solar-only system. Fluorescent luminaries are fixed directly over plants in one hybrid system. Point-source HID lamps are centrally located in the CELSS module with fiber optic light pipes to the plants in the second hybrid system.

Fluorescent fixtures are known technology that will require little additional development for CELSS applications. Excellent light control and distribution is possible with luminares design. Fiber optic terminal illuminators are integrated into luminares (fig. 6.3-3) to conserve mass and volume. Problem areas include: mercury content of lamps; short life span because of rapid on/off cycling; lamp replacement, and mutual interference, which limits close spacing of lamps. Designs created during this study suggest that all of these problems are manageable. For example, mutual interference by flourescent fixtures is eliminated by installing the fiber optic terminal illuminator between them to act as a shield. Solar plus fluorescent use 12-kW peak power (fig. 6.3-2) for illumination. Thermal control adds 2.4 kW and atmosphere control adds 0.7 kW. Total CELSS peak-power consumption is 19.3 kW; about 9% of Space Station available power.

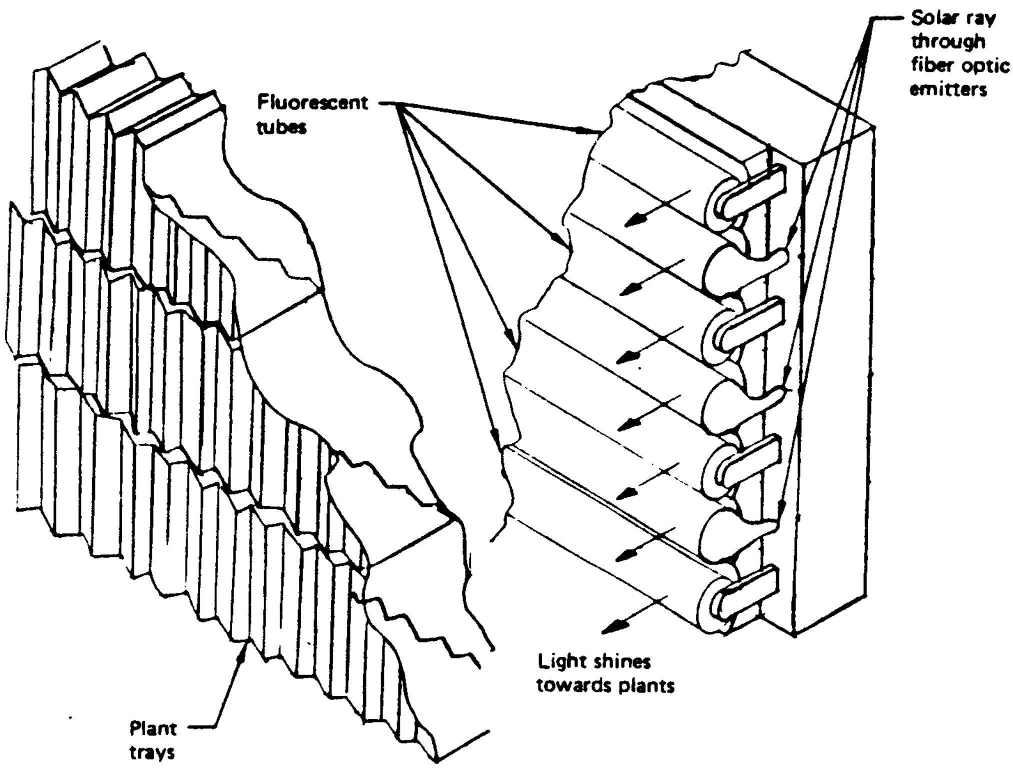


Figure 6.3-3. Combined Solar and Fluorescent

The HID lamp system uses high-pressure sodium lamps enclosed in cylindrical fixtures fitted with focusing lenses (fig. 6.3-4). These lenses focus light onto fiber optic cables that then pipe the light to the plants (fig. 6.3-5). The same terminal illuminators used for solar collectors distribute the light. Subsystem advantages are the high-efficiency lamp, centralized cooling, simplified maintenance and hazardous-material containment.

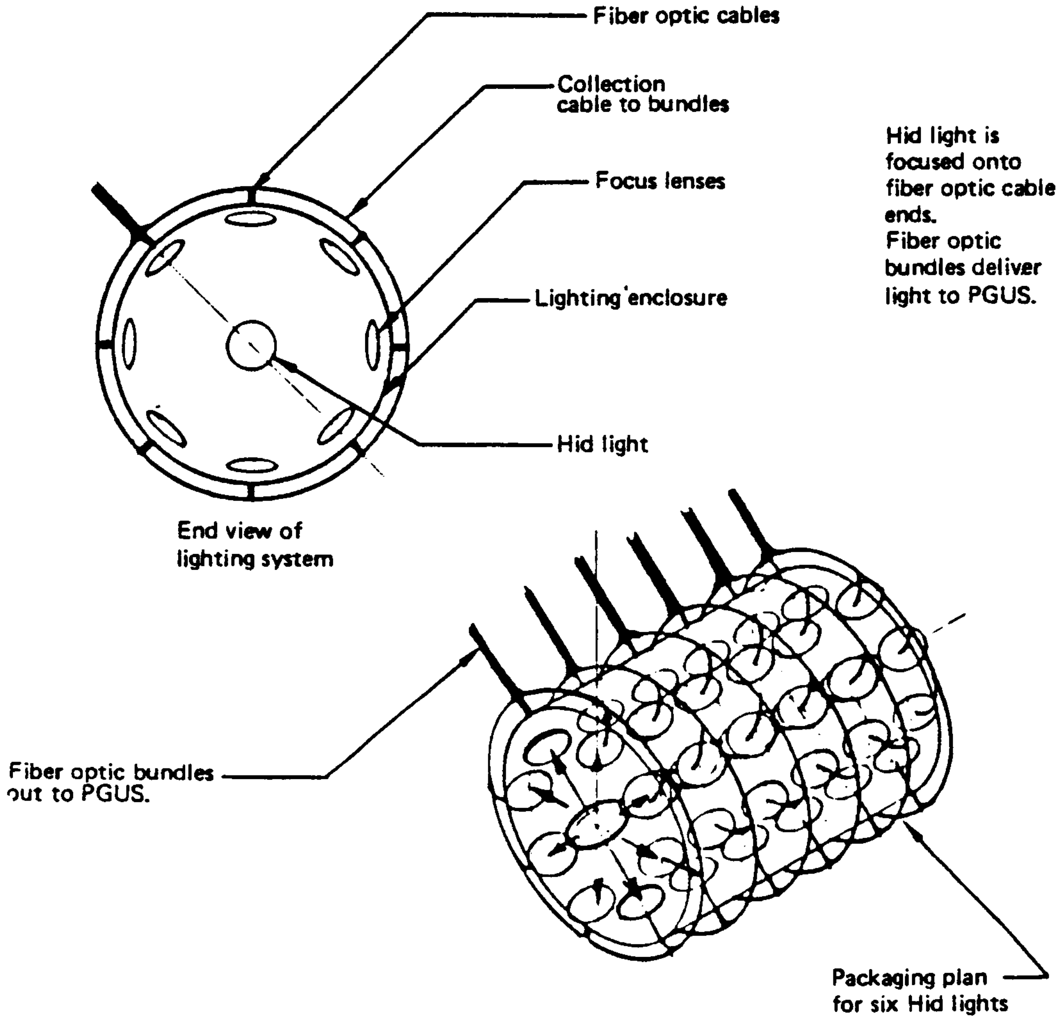


Figure 6.3-4. Hid Lighting System

Problems are light loss at interface with fiber optic cable and the need to preheat lamps. This system uses 11.7-kW peak for illumination (fig. 6.2-1). Thermal control and atmosphere control are 2.4-kW peak and 0.66-kW peak, respectively. Total CELSS module power requirement is 19-kW peak (fig. 6.3-2); about 9% of Space Station available power.

Illumination systems power analysis suggest-

a. Solar-only illuminator provides the best illumination per watt.

b. Hybrid systems are essentially identical in performance.

c. Artificial-only lighting system power demands are prohibitive. Because of the excessive power demand, artificial-only lighting is dropped from further consideration in this study.

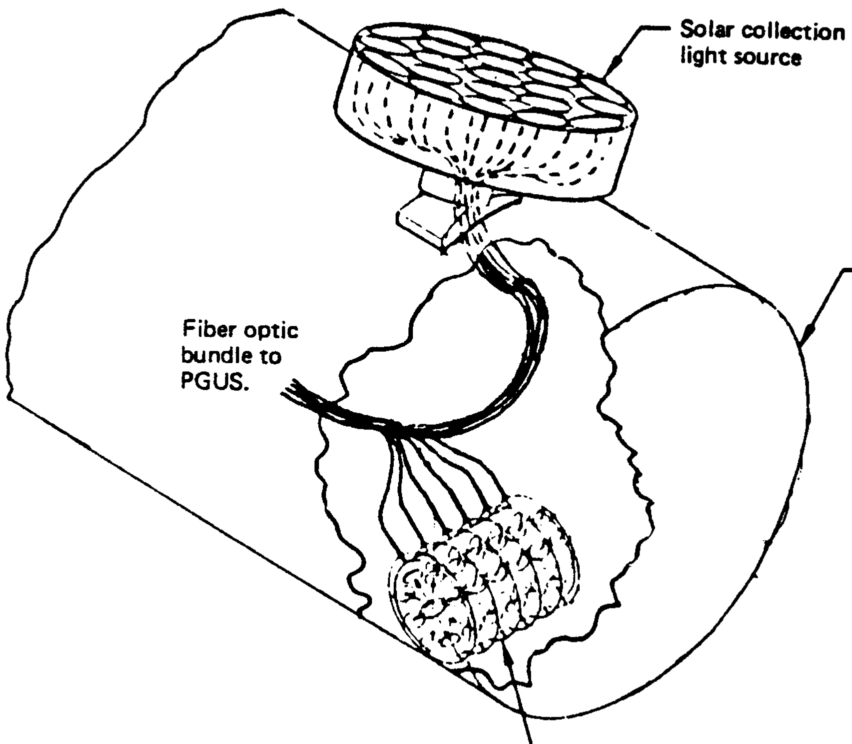


Figure 6.3-5. Combined Solar and Hid Lighting

Further analysis needs to consider power cycles and edible biomass production to verify the analysis. Power cycle analysis is presented in section 6.4. Insufficient information is available to conduct edible biomass production analysis.

Comparing mass of illumination systems (fig. 6.3-6) focuses on the three remaining systems; solar only, solar plus fluorescent, and solar plus HID. The solar collector subsystem has considerable mass (5503 kg; fluorescent subsystem adds 559 kg for a total of 6062 kg; HID subsystem adds 1564 kg, for a total of 7067 kg. Illumination system mass analysis suggest-

a. Solar-only illumination provides best illumination per kilogram

b. Solar plus fluorescent provides best illumination per kilogram for hybrid system.

c. Solar plus HID has highest illumination-to-mass ratio.

Comparing systems on a percentage basis shows that differences range from 10% to 28%.

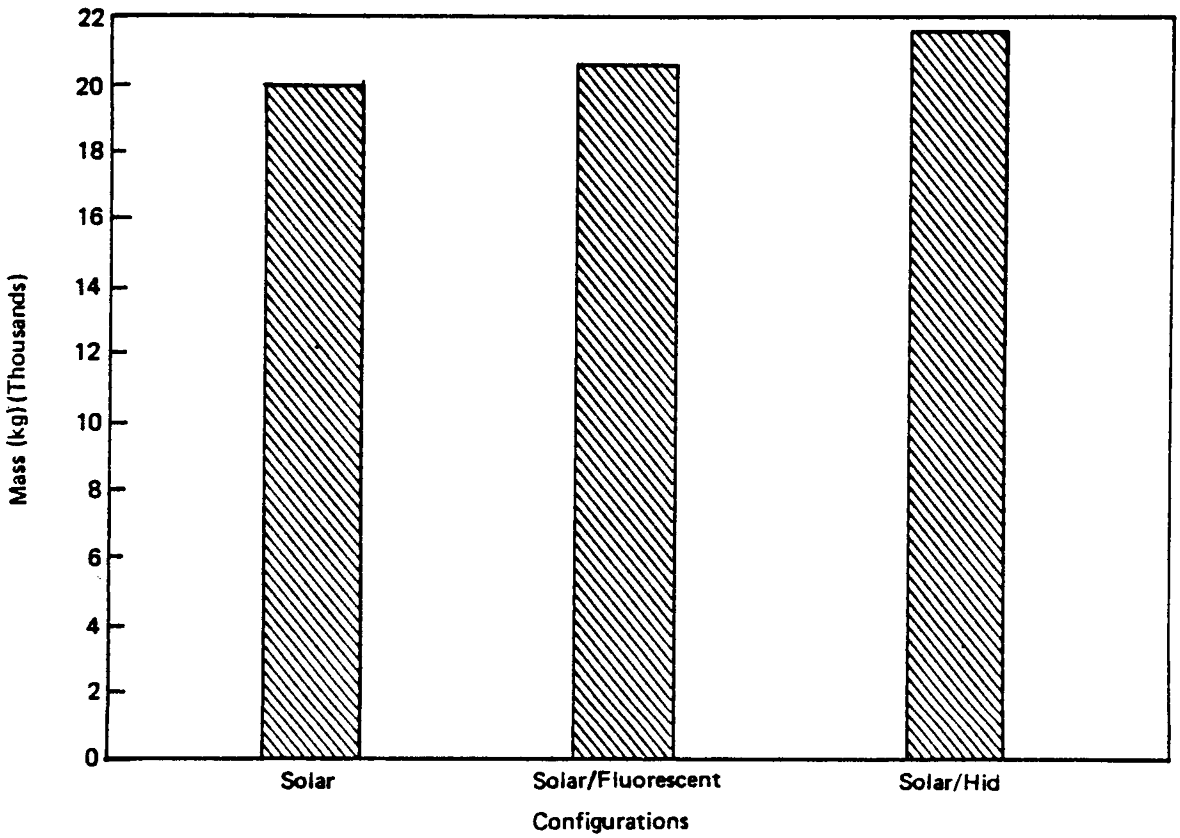


Figure 6.3-6. Illumination System Mass

Table 6.3-1

Option	Solar only	Solar plus fluorescent	Solar plus HID
Solar only	NA	10%	28%
Solar plus flour	10%	NA	17%
Solar plus HID	28%	17%	NA

Cost analysis (fig. 6.3-7) indicates that solar-only system has lowest illumination system cost at $161.2 million. Four percent more will purchase a fluorescent system at $167.3 million. Solar plus HID costs $230.2 million, a 43% increase over solar-only costs. These cost differences reflect the development cost associated with new systems. Solar collector designs exist but must be redesigned to withstand space conditions. Flourescent fixtures already exist in spacecraft and will need little additional development. Using HID with fiber optics is a totally new lighting concept. This concept will suffer high development costs; especially to overcome light losses at junctions. Illumination cost analysis suggests-

a. Solar-only illumination has lowest net cost.

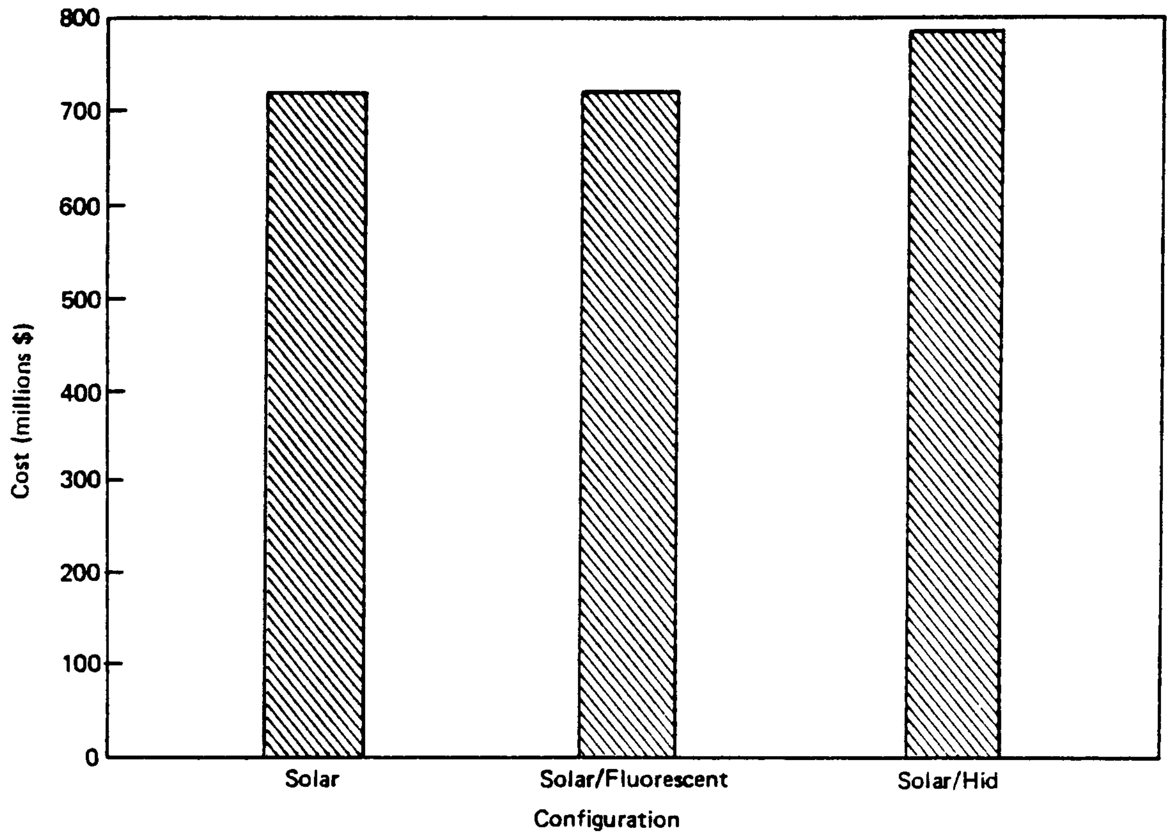


Figure 6.3-7. Illumination System Cost Comparison

b. Solar plus fluorescent cost is marginally higher than solar only.

c. Solar-plus-HID high cost results from extensive development and design work required by this new system.

Volume analysis (fig. 6.3-8) indicates that lowest illumination system volume penalty is the solar-only system. Solar-only system requires 6.8 m^3 internal module volume. Solar plus fluorescent system needs an additional 19% internal volume totaling 8.1 m^3. Solar plus HID is 51% larger than solar only requiring a net internal volume 0f 10.3 m^3.

Illumination volume analysis suggests-

a. Solar-only illumination has lowest net volume.

b. Solar fluorescent has best volume of hybrid systems.

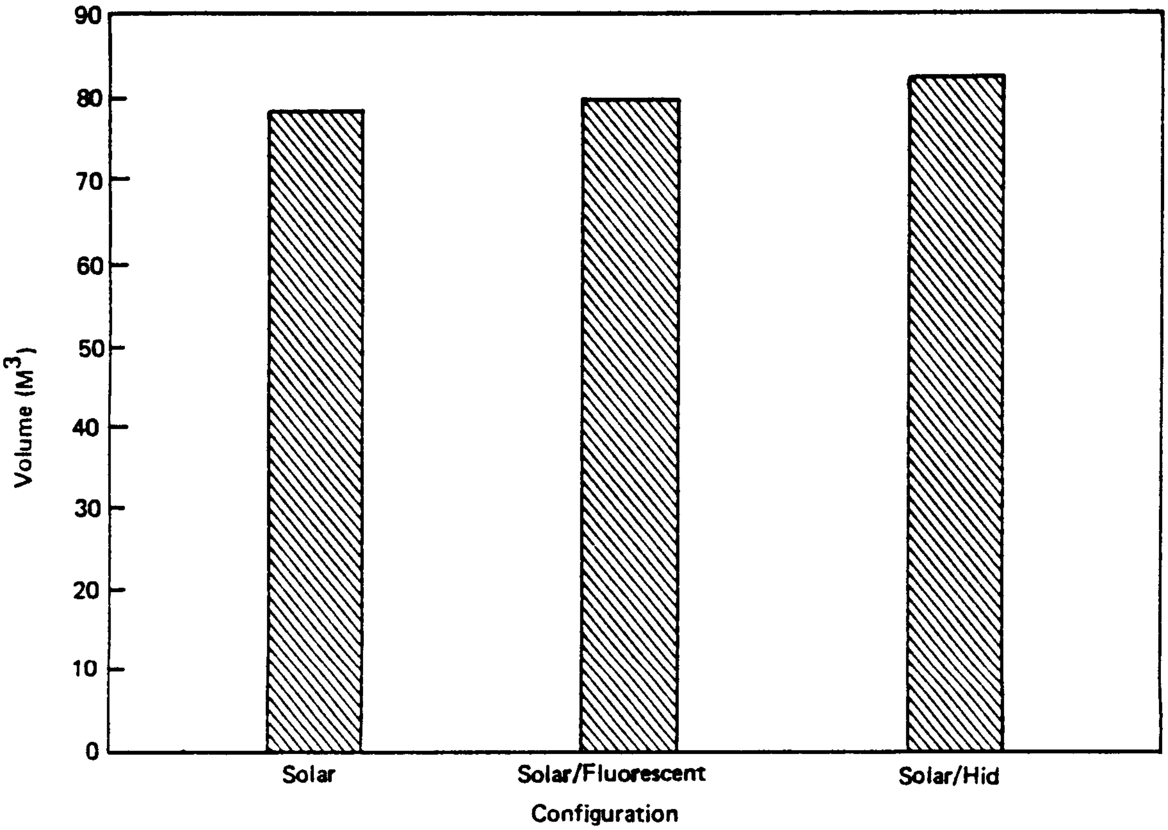


Figure 6.3-8. Illumination System Volume Comparison

c. Solar plus HID system has largest illumination system volume.

CELSS module sensitivity analysis considers the illumination systems plus all additional CELSS systems. Table 6.3-2 summarizes these data.

Table 6.3-2. Illumination System Parametric Comparison

Option	Mass	Power (kW)	Cost (M$)	Volume (m^3)
Solar only	19919	6.8	724	78.1
Solar plus fluorescent	20549	19.2	730	79.4
Solar plus HID	21544	19	793	81.6

Overall, the best choice is solar-only based on parametrics. Solar plus fluorescent is primarily penalized by the power requirement. The other parametric values are too close to call significant. Solar plus HID is marginally better in power but significantly

poorer in mass and cost. This system could become more attractive when improved fiber optics reduce the power requirement. Maintenance, safety, and accessibility factors also favor the HID approach in the hybrid systems. Unanswered plant physiology and morphology questions haunt the solar-only system. Satisfactory plant growth and production under this system would make solar-only the logical choice for CELSS. Several factors need evaluation under the three lighting systems.

a. Growth period to maturity (harvest).
b. Edible biomass production.
c. Oxygen generation levels.
d. Carbon dioxide uptake.
e. Transpiration rates.
f. Nutritional values of edible biomass.

When these factors are known a system selection can be made.

6.4 ELECTRICAL POWER UTILIZATION ANALYSIS

Electrical power may be the most limited service provided by Space Station. CELSS power demand must be tailored to fit station resources. Analyzing electrical power demand requires developing load-cycle flow charts. These load-cycle flow charts combine Space Station operational constraints, how often and how long a system operates, and the loading placed on each system. These factors are plotted out as a function of time to analyze CELSS power demands at any time. The plot is continued until every normal function performed by the CELSS is incorporated at about a 21-hr cycle. This results in every normal power consumption combination being considered in the 21-hr load-cycle flow chart. The time period required for every operation is a power duty cycle. Duty cycles repeat continually until some new power consumption combination is established. Table 6.4-1 is a CELSS load-cycle flow chart using the solar plus fluorescent light system. Figure 6.4-1 plots the total power demand. Examining these charts allows general conclusions about this system. CELSS power demand responds sharply to orbital light/dark cycles. Power demands levels are relatively constant for each orbital phase; the exception is at cycle hour 18. Twenty-one hours forms an electrical power duty cycle during which every normal power-consuming operation occurs.

Table 6.4-1

POWER UTILIZATION PROJECTION CYCLE HOUR: DARK PHASE (****)	.5	1	1.5 ****	2	2.5	3 ****	3.5	4	4.5 ****	5	5.5	6 ****	6.5	7	7.5 ****	8	8.5	9 ****	9.5	10	10.5 ****	11
ATMOSPHERE CONTROL	659	659	457	659	659	457	659	659	457	659	659	457	659	659	457	659	659	457	659	659	457	659
DATA MANAGEMENT	315	315	210	315	315	210	315	315	210	315	315	210	315	315	210	315	315	210	315	315	210	315
FOOD PROCESSING																						
HARVESTER																						
SEEDER																						
ILLUMINATION	375	375	11616	375	375	11616	375	375	11616	375	375	11616	375	375	11616	375	375	11616	375	375	11616	375
NUTRIENT MGT SYS	2540	2540	360	2540	2540	360	2540	2540	360	2540	2540	360	2540	2540	360	2540	2540	360	2540	2540	360	2540
ROBOTICS	193	193	0	193	193	0															0	193
WASTE REGENERATION																						
SUBTOTAL	4082	4082	12643	4082	4082	12643	3889	3889	12643	3889	3889	12643	3889	3889	12643	3889	3889	12643	3889	3889	12643	4082
THERMAL CONTROL	2242	2242	1220	2242	2242	1220	2231	2231	1220	2231	2231	1220	2231	2231	1220	2231	2231	1220	2231	2231	1220	2242
HOUSEKEEPING	204.1	204.1	632.15	204.1	204.1	632.15	194.45	194.45	632.15	194.45	194.45	632.15	194.45	194.45	632.15	194.45	194.45	632.15	194.45	194.45	632.15	204.1
TOTALS	6528	6528	14495	6528	6528	14495	6314	6314	14495	6314	6314	14495	6314	6314	14495	6314	6314	14495	6314	6314	14495	6528
RUNNING AVERAGE	6528	6528	9184	9184	9184	9184	9113	9041	9041	9041	9041	9041	9041	9041	9041	9041	9041	9041	9041	9041	9041	9113

Table 6.4-1 (continued)

11.5	12 ****	12.5	13	13.5 ****	14	14.5	15 ****	15.5	16	16.5 ****	17	17.5	18 ****	18.5	19	19.5 ****	20	20.5	21 ****	LIGHT AVERAGE	DARK AVERAGE	GROSS AVERAGE
659	457	659	659	457	659	659	457	659	659	457	659	659	457	659	659	457	659	659	457	659	457	592
315	210	315	315	210	315	315	210	315	315	210	315	315	210	315	315	210	315	315	210	315	210	280
	0	700	700																	50	0	467
	0	300	300																	21	0	200
				0	200	200	0	200												21	0	120
375	11616	375	375	11616	375	375	11616	375	375	11616	375	375	11616	375	375	11616	375	375	11616	375	11616	4122
2540	360	2540	2540	360	2540	2540	360	2540	2540	360	2570	2540	360	2540	2540	360	2540	2540	360	2541	360	1814
193	0	193	193	0	193	193	0	193	193	0	193	193	0							97	0	123
														565	1173	1173	1173	1173	1173	328	168	1919
4082	12643	5082	5082	12643	4282	4282	12643	4282	4082	12643	4112	4082	12643	9540	5062	13816	5062	5062	13816	4407	12811	7208
2242	1220	2253	2253	1220	2242	2242	1220	2242	2242	1220	2242	2242	1220	2295	2253	1231	2253	2253	1231	2242	1222	1902
204.1	632.15	254.1	254.1	632.15	214.1	214.1	632.15	214.1	204.1	632.15	205.6	204.1	632.15	477	253.1	690.8	253.1	253.1	690.8	220	641	360
6528	14495	7569	7589	14495	6738	6738	14495	6738	6528	14495	6560	6528	14495	12312	7568	15738	7568	7568	15738	6869	14673	9470
9184	9184	9537	9891	9891	9607	9324	9324	9324	9254	9254	9194	9194	9194	11112	11458	11873	10291	10291	10291			

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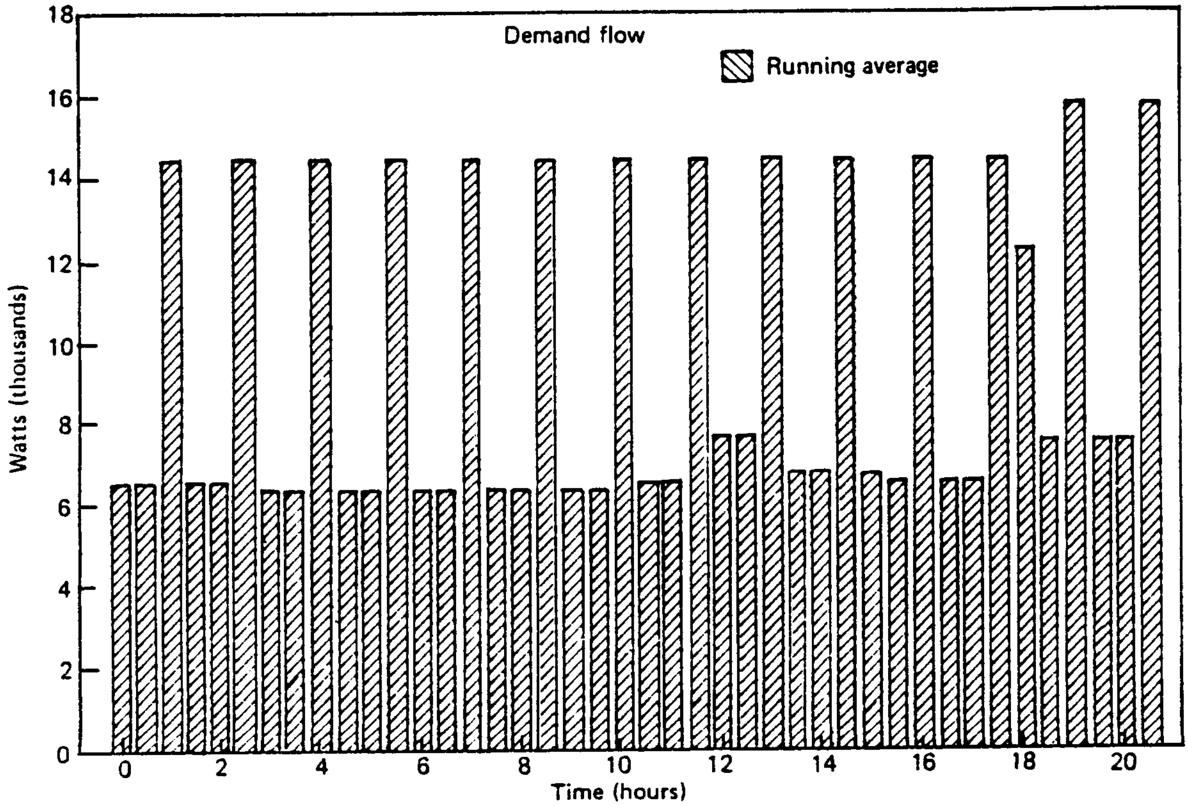

Figure 6.4-1. Electrical Power Load Cycle

Detailed load-cycle flow chart examination reveals the factors that determine total power demand. Illumination has minimal impact on light-side power demand. This low demand results from using solar collectors for lighting. These collectors require only 373W to capture 8 mill lumens. This 373W drives the lens-pointing system that maintains optimum collector orientation. Sun-side thermal control and atmosphere control are relatively high values as they remove the heat imported by direct solar illumination. Light-side total CELSS power demand averages about 6.8 kW.

Artificial lighting, even at one-tenth intensity, creates a heavy power draw during dark-side operations. This draw averages about 11.6 kW. Thermal and atmosphere control average of CELSS dark-side power draw is about 14.5 kW. This equates to 7% of Space Station power for CELSS dark-side operation using fluorescent low-intensity illumination.

Power perturbations occur as CELSS supporting systems are activated to perform their tasks. All possible supporting tasks were scheduled during light-side operations for preparing this load cycle flow chart. This practice conserved Space Station stored power during dark-side operations. For example, robotic gardener activates at hour 11 and

operates during orbital light cycles until hour 17.5. During this period additional power demands are crated when the harvester and food processor operate on plants collected by robotic gardener.

The Supercritical water oxidation system startup creates the largest CELSS power perturbation at hour 18.5. During this half-hour light-side period, the SCWO reaction chamber is heated to initiation temperature. Subsequent SCWO reactions are exothermic requiring no additional chamber heating. High-pressure compressors are required to sustain reactant flow into the reaction chamber. These compressors operate continuously through light and dark cycles for 2.5 hr until cycle hour 21. SCWO impact on thermal control is minimized through a highly efficient liquid cooling subsystem.

CELSS module overall power loading ranges from 6.3 kW to 15.7 kW with the highest draw during dark-side orbit. Average CELSS power demand is about 9.4 kW for both dark and light cycles. A three datum running average is calculated for this example system (table 6.4-1). The running average is plotted in figure 6.4-2. The graph suggests that sustained power draw from Space Station can be held to 9.5 kW. This approach requires a power storage device on the CELSS module. A power storage device imposes volume, cost, and weight penalties but can reduce limitations created by dark-side power surge demands on the Space Station.

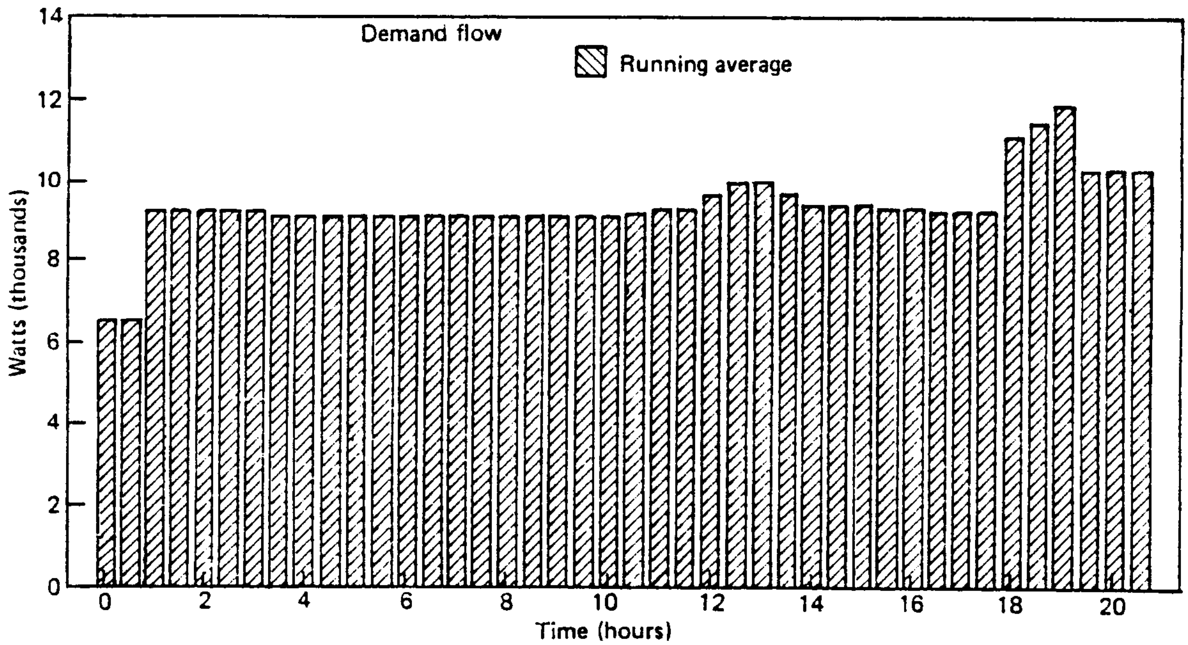

Figure 6.4-2. CELSS Running Average Power

An alternative approach to reducing power peaking is to alter system operations. This rescheduling approach may optimize system operational periods and loading to minimize power demand fluctuations. For example, shutting off lights during SCWO system operation reduces power consumption by up to 1.8 kW light side and up to 12 kW dark side. Arranging this action to coincide with a plant's photoperoid can save power without reducing yield. Load cycle flow charts provide a means to examine this type of power demand rearrangement.

6.5 CROP-MIX ANALYSIS

Mixed crop systems are needed to support long durations, manned space flight. These crops must be highly efficient in light utilization and provide a balanced diet. This crop mix sensitivity analysis examines representative plant species effect on CELSS. Three representative crop species are used in this study to examine plant species selection effect on CELSS. These selected species were chosen for two purposes.

a. The species provide physical dimension models for a grass (wheat), legume (soybean), and tuber (potato) to use during preliminary design.

b. The species model plant productivity effects on CELSS parametric values. Plant dimension effects on preliminary design are discussed in section 4.0. The plant dimension variations required extensive flexibility in plant growth unit, robot, harvester, food processor, structures, and illumination design. Systems less affected are those that provide supporting services, such as atmosphere control, thermal control, and storage.

Productivity effects on parametrics examines three crop characteristics.

a. Edible biomass produced per unit volume (m^3).

b. Growth period from planting to harvest.

c. Biologically recoverable calories per gram of dry edible biomass.

Usable calories per day per unit volume (daily yield) is determined by these three characteristics.

Edible plant biomass used in this study are the wheat berry, soybean berry, and potato tuber. Although some other parts of each plant may be edible it would require secondary processing technology that is not currently identifiable. Growth period used is for optimum growing conditions with illumination adjusted for maximum yield at maturity. Period selected results in a maximum biomass production per growth day. Crops may be harvested green (soybean) and dried using waste heat from thermal control system. Biologically recoverable calories are those that can be obtained from the crop edible parts by a human eating a balanced diet. For example, wheat eaten alone yields about 3.3 cal/g, but when eaten as part of a balanced diet yields about 3.7 cal/g.

Analysis demonstrates that increased CELSS volume requirements results from reduced yield per unit area, longer growth periods, or decreased calories per gram of edible biomass. For example, increasing the wheat growth cycle from 62 to 85 days reduces edible biomass harvested per square meter per day by a proportionate amount (37%). To compensate, larger areas are harvested, which in turn requires more PGUs. Each PGU adds 1.71 m^3 to CELSS volume. This increase in growth period may also increase total power requirements because a larger system maintenance overhead occurs with larger modules.

Multiple variations in productivity factors result in algebraic, not additive, changes in daily yield. For example, table 6.5-1 contains productivity values for wheat, soybean, and potatoes.

Table 6.5-1. Productivity Figures

	cal/G	gram/m2	cycle	Increment
Wheat	3.6 (100%)	2400 (100%)	62 (100%)	1.0
Soybean	4.0 (111%)	950 (39.6%)	100 (161%)	5.9
Potato	3.7 (102%)	3275 (136%)	115 (185%)	1.3

Using wheat as a baseline (increment = 1), a quick examination shows that soybeans require about 5.9 times the volume as wheat, and potatoes require 1.3 times the volume as wheat to produce the same daily yield. Major differences in daily yield are caused by the compounding of the effect of differences in each productivity value. These productivity differences effect on the CELSS module are examined in a crop-mix

analysis (table 6.5-2). This analysis relates the proportion of each type crop grown to the parameters for the CELSS module required to support the crop mix. A 100% wheat crop (set 1 on table 6.5-2) uses 79.8 m^3 of module volume, crop 8.5 kW of power. A change to 100% soybeans results in a need for 342 m^3 and 28 kW of power. This is a difference of 420% for volume and 329% for power. This is not the predicted 590% increase because some of the costs are absorbed in the overhead penalty common to all systems. It does demonstrate rapid changes in parameters that can occur with a change in crop. The analysis also shows that when crops with similar productivity values are mixed (50% wheat, 50% potatoes, table 6.5-2) the changes in module parameters are relatively minor. Table 6.5-2 presents eight crop-mix variations. These scenarios are graphically compared in figures 6.5-1 through 6.5-4 for each parameter.

The results of this analysis supports a case for intense research into three areas to improve CELSS productivity.

a. Screen plants of the world for very high productivity crops. Identifying several plants that can best provide the human nutritional needs, while retaining high productivity, is essential to practical higher plant CELSS development.

b. Inedible-to-edible biomass conversion procedures and equipment will improve daily yields. Commonly used crop species have a high proportion of inedible biomass. This figure often exceeds 50% and may be higher. Converting this inedible biomass into a food material can effectively double daily yield.

c. Examine single cell organisms for species that can supplement a diet based on a few higher plants. These organisms would be used to provide essential nutrients available only in very small amounts in higher plants. Genetic manipulation may be required to develop the species characteristics desired.

CALS/GRAM		CAL/DAY=	2800.0	GRAM/M2		HGH (CM)	GROWTH CYCLE	
WHEAT=	3.6			WHEAT=	2400.0	50.0	WHEAT	62.0
SOYBEANS=	4.0	M2/PGU=	1.7	SOYBEANS=	950.0	130.0	SOYBEANS	100.0
POTATOES=	3.7	PERSONS=	2.0	POTATOES=	3275.0	90.0	POTATOES	105.0

SET 1 EVALUATION										
% CALS FROM		CALS REQ	AREA REQ	PGU's REQ		PGU VOL	PGU PWR	MODULE VOLUME=	79.8	(CUBIC METERS)
WHEAT	100%	5600.0	40.2	24.2		41.4	8523.7	MODULE POWER=	8.5	(KILOWATS)
SOYBEANS	0%	0.0	0.0	0.0		0.0	0.0	MODULE MASS	20549.0	(KILOGRAMS)
POTATOES	0%	0.0	0.0	0.0		0.0	0.0	MODULE COST=	730.2	(K DOLLARS)
TOTALS	1.0	5600.0 (CALS)	40.2 (M2)	24.2	PGU's	41.4 (M3)				
SET 2 EVALUATION										
% CALS FROM		CALS REQ	AREA REQ	PGU's REQ		PGU VOL	PGU PWR	MODULE VOLUME=	342.1	(CUBIC METERS)
WHEAT	0%	0.0	0.0	0.0		0.0	0.0	MODULE POWER=	28.0	(KILOWATS)
SOYBEANS	100%	5600.0	146.3	88.1		267.7	28014.0	MODULE MASS	57366.0	(KILOGRAMS)
POTATOES	0%	0.0	0.0	0.0		0.0	0.0	MODULE COST=	2453.0	(K DOLLARS)
TOTALS	1.0	5600.0 (CALS)	146.3 (M2)	88.1	PGU's	267.7 (M3)				
SET 3 EVALUATION										
% CALS FROM		CALS REQ	AREA REQ	PGU's REQ		PGU VOL	PGU PWR	MODULE VOLUME=	111.7	(CUBIC METERS)
WHEAT	0%	0.0	0.0	0.0		0.0	0.0	MODULE POWER=	12.4	(KILOWATS)
SOYBEANS	0%	0.0	0.0	0.0		0.0	0.0	MODULE MASS	24744.0	(KILOGRAMS)
POTATOES	100%	5600.0	48.1	29.0		68.8	12357.0	MODULE COST=	984.8	(K DOLLARS)
TOTALS	10	5600.0 (CALS)	48.1 (M2)	29.0	PGU's	68.8 (M3)				
SET 4 EVALUATION										
% CALS FROM		CALS REQ	AREA REQ	PGU's REQ		PGU VOL	PGU PWR	MODULE VOLUME=	93.4	(CUBIC METERS)
WHEAT	95%	5320.0	38.2	23.0		39.3	8097.5	MODULE POWER=	9.5	(KILOWATS)
SOYBEANS	5%	280.0	7.3	4.4		13.4	1400.7	MODULE MASS	22606.0	(KILOGRAMS)
POTATOES	0%	0.0	0.0	0.0		0.0	0.0	MODULE COST=	865.0	(K DOLLARS)
TOTALS	1.0	5600.0 (CALS)	45.5 (M2)	27.4	PGU's	52.7 (M3)				
SET 5 EVALUATION										
% CALS FROM		CALS REQ	AREA REQ	PGU's REQ		PGU VOL	PGU PWR	MODULE VOLUME=	81.2	(CUBIC METERS)
WHEAT	95%	5320.0	38.2	23.0		39.3	8097.5	MODULE POWER=	8.7	(KILOWATS)
SOYBEANS	0%	0.0	0.0	0.0		0.0	0.0	MODULE MASS	21692.0	(KILOGRAMS)
POTATOES	5%	280.0	2.4	1.4		3.4	617.8	MODULE COST=	797.6	(K DOLLARS)
TOTALS	1.0	5600.0 (CALS)	40.6 (M2)	24.4	PGU's	42.8 (M3)				
SET 6 EVALUATION										
% CALS FROM		CALS REQ	AREA REQ	PGU's REQ		PGU VOL	PGU PWR	MODULE VOLUME=	120.1	(CUBIC METERS)
WHEAT	50%	2800.0	20.1	12.1		20.7	4261.9	MODULE POWER=	12.0	(KILOWATS)
SOYBEANS	10%	560.0	14.6	8.8		26.8	2801.4	MODULE MASS	24744.0	(KILOGRAMS)
POTATOES	40%	2240.0	19.3	11.6		27.5	4942.8	MODULE COST=	984.8	(K DOLLARS)
TOTALS	1.0	5600.0 (CALS)	54.0 (M2)	32.5	PGU's	75.0 (M3)				
SET 7 EVALUATION						PGU VOL	PGU PWR	MODULE VOLUME=	122.8	
% CALS FROM		CALS REQ	AREA REQ	PGU's REQ		16.6	3409.5	MODULE POWER=	12.4	(CUBIC METERS)
WHEAT	40%	2240.0	16.1	9.7		26.8	2801.4	MODULE MASS	24744.0	(KILOWATS)
SOYBEANS	10%	560.0	14.6	8.8		34.4	6178.5	MODULE COST=	984.8	(KILOGRAMS)
POTATOES	50%	2800.0	24.1	14.5						(K DOLLARS)
TOTALS	1.0	5600.0 (CALS)	54.8 (M2)	33.0	PGU's	77.7 (M3)				
SET 8 EVALUATION						PGU VOL	PGU PWR	MODULE VOLUME=	95.8	
% CALS FROM		CALS REQ	AREA REQ	PGU' REQ		20.7	4261.9	MODULE POWER=	10.4	(CUBIC METERS)
WHEAT	50%	2800.0	20.1	12.1		0.0	0.0	MODULE MASS	22606.0	(KILOWATS)
SOYBEANS	0%	0.0	0.0	0.0		34.4	6178.5	MODULE COST=	865.0	(KILOGRAMS)
POTATOES	50%	2800.0	24.1	14.5						(K DOLLARS)
TOTALS	1.0	5600.0 (CALS)	44.2 (M2)	26.6	PGU's	55.1 (M3)				
SET 9 EVALUATION						PGU VOL	PGU PWR	MODULE VOLUME=	165.8	
% CALS FROM		CALS REQ	AREA REQ	PGU's REQ		10.3	2130.9	MODULE POWER=	15.3	(CUBIC METERS)
WHEAT	25%	1400.0	10.0	6.1		66.9	7003.5	MODULE MASS	28683.0	(KILOWATS)
SOYBEANS	25%	1400.0	36.6	22.0		34.4	6178.5	MODULE COST=	1226.3	(KILOGRAMS)
POTATOES	50%	2800.0	24.1	14.5						(K DOLLARS)
TOTALS	1.0	5600.0 (CALS)	70.7 (M2)	42.6	PGU's	111.7 (M3)				

Table 6.5-2. Crop Mix Analysis

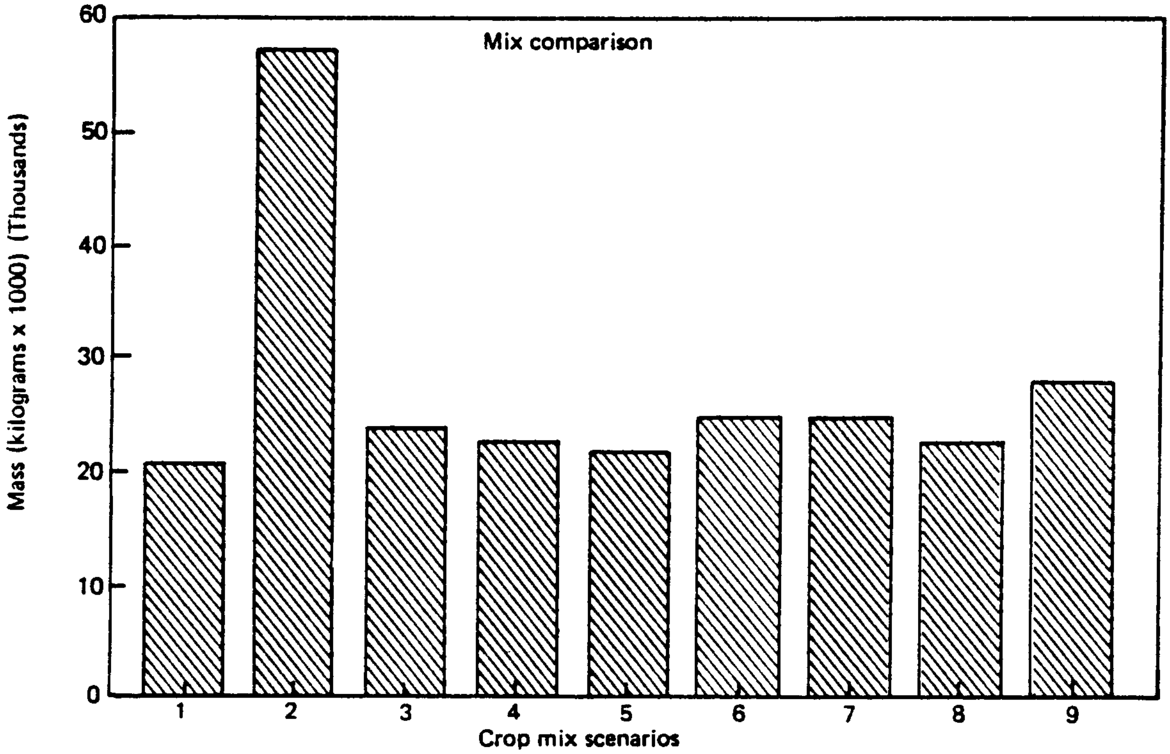

Figure 6.5-1. CELSS Crop Mix Mass Comparison

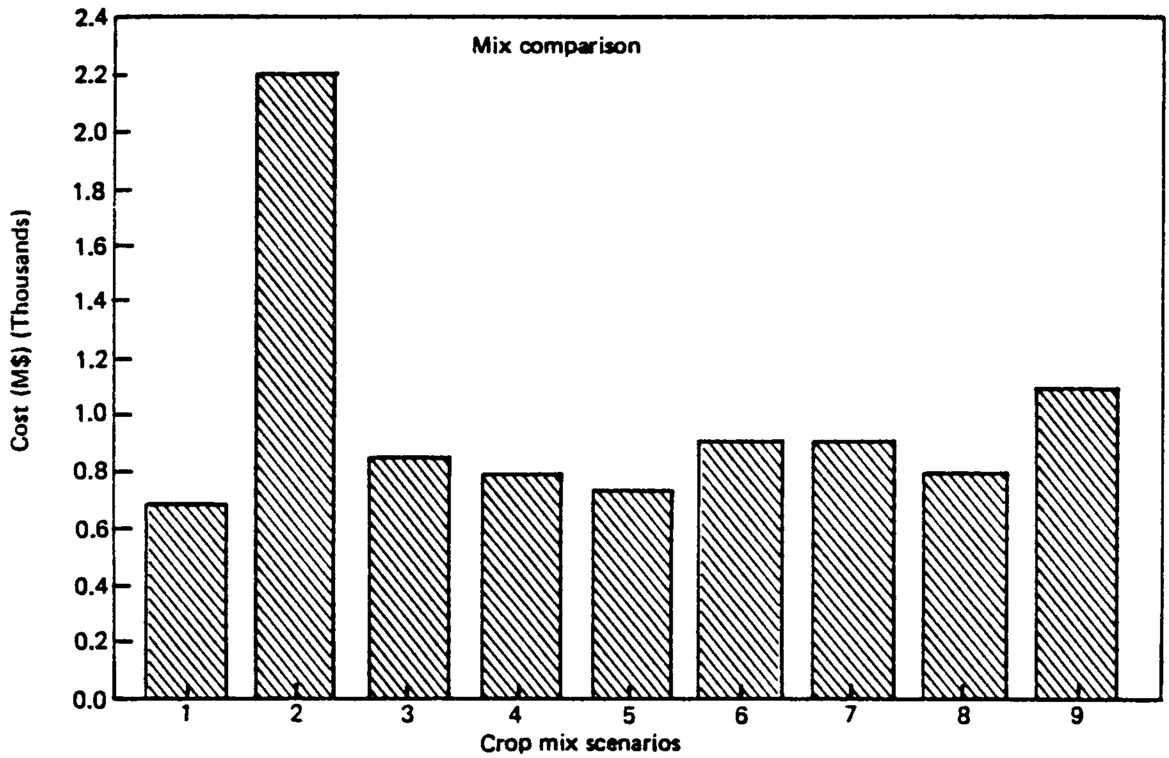

Figure 6.5-2. CELSS Crop Mixes

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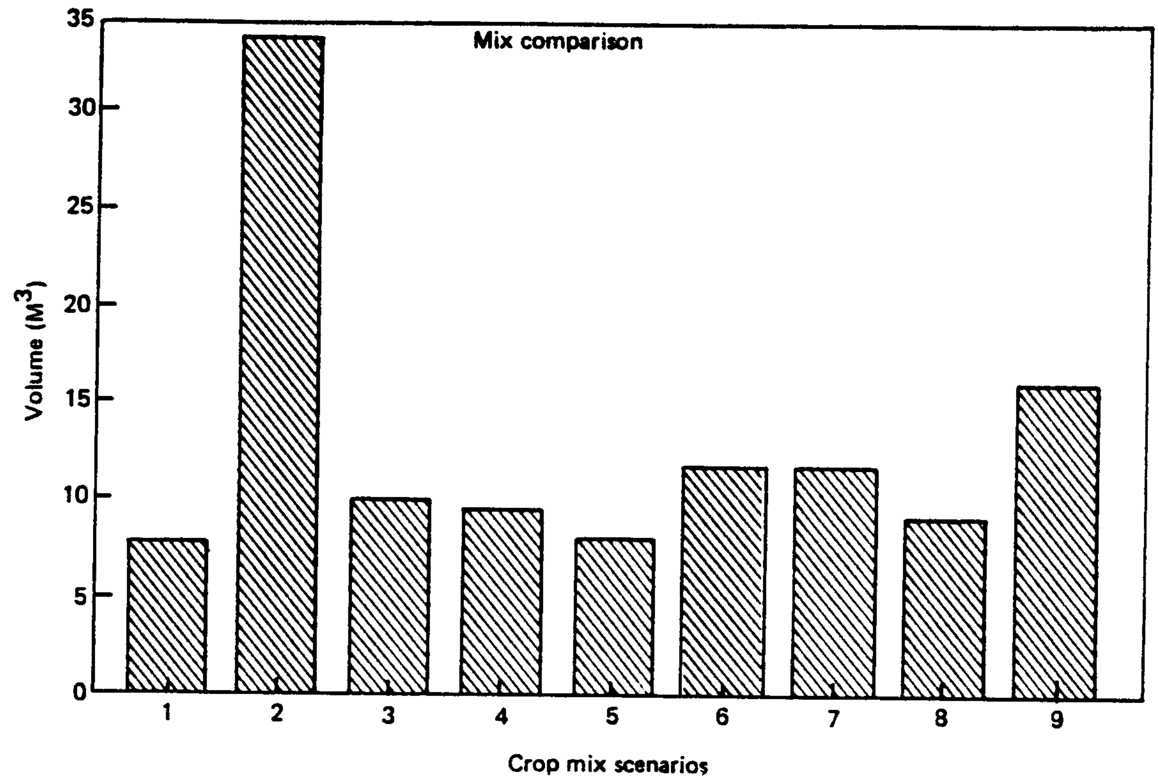

Figure 6.5-3. CELSS Crop Mixes (Volume)

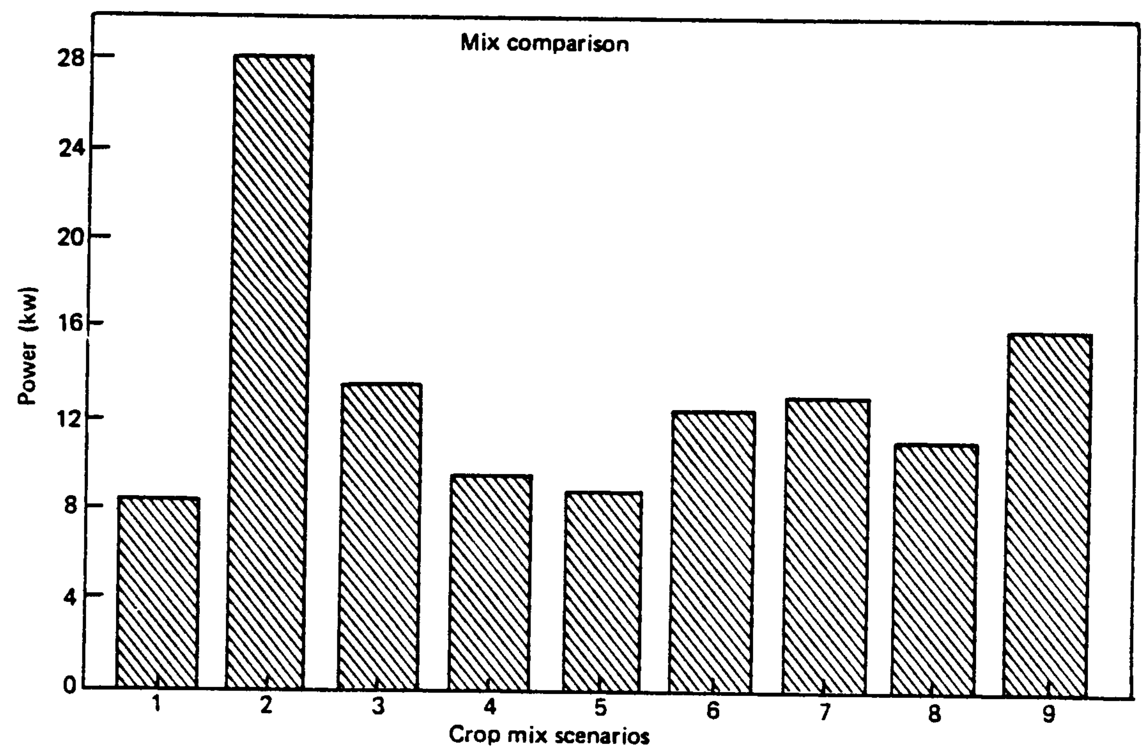

Figure 6.5-4. CELSS Crop Mixes

7.0 RESEARCH AREAS

Major increases in CELSS data base are necessary for full-scale CELSS module development. Research programs are needed to develop this data base. Biological, engineering, and technology areas that need additional research were identified during this study. Significant differences in the study results can occur as values become more concrete. For example, increased effectiveness in collecting direct solar energy may reduce weight, cost, power, and design complexity. Even known values in many areas are based on 1g experience and may change in a microgravity environment. For example, plant size and growth characteristics are unknown for microgravity conditions. Even a modest increase in plant size can add significant volume to the PGUs.

A research area compilation is provided in this section to aid the reader in understanding the unknown aspects of the CELSS. This listing identifies areas within which are many specific research topics. A detailed listing is too long and tedious to meet the purpose of this study. Three categories are identified:

a. Biological Research Areas - Research areas involving the growth, morphology, nutrition, reproduction, or culture of plants in a microgravity environment. For example, genetic engineering plant species to provide improved nutrition.

b. Engineering Research Areas - Research areas involving the construction, design, material, and integration of CELSS materials and equipment. For example, PGU design to support plants with highly divergent morphological configurations.

c. Advanced Technology Research Areas - Research areas involving the development of currently unavailable equipment, procedures, techniques, or materials. For example, developing a nonphytotoxic structural plastic that does not create a significant off-gassing problem and is useable with plant nutrient solutions.

Each research area entry follows the same general format: (1) entry identification number; (2) suggested research area described; (3) parameters affected (electrical power, mass, volume, cost) and/or other considerations identified.

This listing is intended to aid CELSS researchers to target their work. When evaluating these suggested research areas, consider the inherent vehicle limitations. The limitations of a space vehicle/station are primarily in electrical power and volume. Additional considerations are resupply and initial launch masses. Cost presents a constraining aspect of any design, thus affecting CELSS operations.

Research listings generated in any study are inherently incomplete. Readers are encouraged to submit any other suggested research areas to the National Aeronautics and Space Administration, Ames Research Center, Moffett Field, California, Attention: Dr. R. MacElroy.

7.1 BIOLOGICAL RESEARCH AREAS

1. Determine plant growth dimensions in microgravity environment. Volume is a function of plant size and yield per plant. Plant growth unit, lighting system, and robotics are primarily affected. Thermal control and atmosphere control may be impacted.

2. Determine edible biomass production per unit area in microgravity environment for edible plants. Volume is a function of the unit area yield and the volume of equipment required to support each unit area. PGU and lighting are primarily affected. Thermal control may be impacted.

3. Develop biologically based inedible-to-edible biomass conversion systems. Volume can be reduced when biomass utilization is improved. Energy requirements may be reduced if a low energy, biologically based system performs the conversion process. Food processing and waste regeneration systems are primarily affected. Lighting system and thermal control are impacted.

4. Determine artificial gravity requirement for plant development in microgravity. Volume and power required per person will significantly increase if a centrifuge device is needed. All CELSS systems are affected by artificial gravity requirements.

5. Evaluate aeroponic plant growth in microgravity. Aeroponics may reduce mass and volume while reducing plant handling problems. The feasibility of this technique in microgravity is in question. Also, certain plants (i.e. potatoes) do not develop properly with current aeroponic techniques.

6. Examine orbital light/dark cycles effect on plant development. Lighting, power, thermal, and volume requirements are impacted by any requirement to provide illumination during orbital dark phase. Effects on yield, flower/seed development, and maturation time are needed to support electrical power versus volume trades.

7. Determine light levels necessary to maintain plant photoactivity while in orbital dark phase. Lower light levels will reduce electrical power and fuel cell requirements. Maintaining plant photoactive state during dark phase may support high yields and rapid maturation compared with total darkness during the dark phase.

8. Lighting requirements for optimum plant growth in CELSS. The trade between high energy use with high light levels in densely packed plants versus using lower energy levels for lower light levels in moderately densely packed plants affects all aspects of CELSS system design.

9. Determine lighting characteristics to orient plant growth through phototropic response in microgravity. Light provides the simplest system to induce plants to grow in a predetermined direction. Alternative growth orientation procedures (e.g., electrical fields, chemical sprays, agitation, etc.) add complexity to the CELSS design. Nonoriented plant growth may make CELSS a nonviable option using higher plants.

10. Develop cultivars with maximum yield per kilowatt of light for desirable plant species. Lighting consumes most CELSS module power and creates the largest heat load. Improved edible return per watt decreases net power consumption and corresponding power required to remove excess heat. Increased yields will also reduce volume requirements provided maturation periods remain constant.

11. Develop cultivars with optimum physical configuration for CELSS PGUs. A short, dense growth plant with small root mass appears to be the optimum plant configuration. Short plants reduce the light source height above the tray surface decreasing the net plant growth unit volume. The denser the plant, the less growth area required for a given number of plants. Short roots decrease tray depth, thus reducing net PGU volume.

12. Develop cultivars that mature earlier while producing full edible biomass for desired plant species. Earlier maturity dates increase pgu production per unit time. Increased production decreases net volume requirements. Electrical power decreases may also occur with fewer plant growth units required.

13. Identify all edible plant species that may be CELSS compatible. Investigate each plant, evaluating its nutritional return and growth characteristics. All parameters are affected by plant selection. For example, reduced power consumption may result from selecting a plant with high edible biomass to power consumption ratio. Volume reductions occur with plants that produce more biomass per unit volume.

14. Develop biologically based inedible-to-edible plant biomass conversion processes. Volume and power savings are possible when the 40%, or more, of inedible biomass is converted into edible matter. Inedible biomass require significant power and volume to grow while in pursuit of edible biomass. The inedible biomass may contain as much energy value as the edible portion. A simple biological system could be very effective in recovering the inedible biomass, using little power and limited volume.

15. Develop a micromoles-to-lumen conversion table. Major difficulty exist in relating micromoles (a biological measure) to lumens (an engineering measure). Engineering design work requires conversion tables to determine the most effective configurations.

16. Determine minimum photosynthetic maintenance light levels. Electrical power requirements are reduced by using low light levels to hold plants in a photosynthetic state during the orbital dark-side. Station mass and volume are reduced as additional fuel cells and supporting solar panels are not required to maintain high artificial light levels. Electrical power requirements are feasible when low-level dark phase lighting is combined with a direct solar illumination device.

17. Determine strobe lighting effects on plant growth. Power, mass, and volume reductions are possible when a single illumination source is used to briefly illuminate each plant tray on a cyclic basis. Cycle time, illumination period, effects on plant physiology, reproduction, and morphology need to be evaluated. Orbital dark-side illumination parameters would benefit from a strobe system generating low net light intensities.

18. Evaluate effects caused by absence of UV and/or IR light. Fiber optic cable and direct solar light collector design will essentially eliminate the UV and IR frequencies. Preliminary work by Dr. Kei Mori suggests major plant growth improvements under these conditions. Volume and mass reductions can occur with improved plant growth.

19. Develop techniques for stimulating directional plant growth (stems up and roots down) in absence of gravity. PGU and lighting system designs are predicated on Earth-like plant growth pattern. Any pattern variation may alter designs and their related parametric values. Orientation phototrophism was assumed in this study. Alternative approaches using chemicals, vibration, magnetic fields, or moisture gradients should be examined.

20. Determine stem, leaf, and root temperatures for optimum edible biomass production. Temperature requirements affect thermal control, mass, and volume by modifying the CELSS and nutrient supply system design. Temperature requirements will affect lighting to plant canopy distances in some configurations. This will affect the PGU volume.

21. Determine transpiration rates for plants grown under high light intensity, high humidity, high CO2 conditions of a CELSS system. ECLSS, thermal control and nutrient supply systems design are dependent on plant transpiration rate. Higher transpiration rates increase ECLSS efficiency, reducing power requirements. These rates increase system volume and power with larger nutrient supply systems.

22. Integrate plant growth factors to produce the maximum edible biomass with the least power. The factors are nutrient supply, CO2 levels, humidity, stem and root temperatures, oxygen levels, air flow rates , light frequencies, and light intensity.

Plant dynamic interaction requires that all factors are integrated in determining optimum CELSS growth conditions. Electrical power availability currently imposes the greatest limitation on the CELSS. Configuring plant growth conditions for minimal power provides the greatest benefit to CELSS concept.

23. Determine nutrient recycle period to support optimum plant growth. Power and mass are affected by the recycle period. Frequent recycling requires added power to the SCWO system. Nutrient makeup (chemical mass) increases with frequent recycling. Growth versus nutrient age data are needed to conduct trades to optimize the CELSS system.

24. Determine light intensity and frequency requirements for each day of plant growth. Electrical power reductions are possible when light intensity and frequency are tuned to plant requirements. For example, low light levels during early growth stages may not affect final yield and could result in a more compact plant.

25. Determine germination conditions necessary in microgravity. Plant incubators, small centrifuges, may be necessary for plant germination. Volume, power, and mass increases would occur with this additional equipment. Human involvement would increase to accommodate plant tending complexity.

26. Determine optimum plant density for aeroponic growth under microgravity conditions. Yields are affected by plant density under identical conditions. CELSS volume requirements are favored by high plant densities.

27. Breed or genetically engineer plants to eliminate adverse flavors, inhibitors, aromas, and textures. Parametric values are not directly affected, but crew acceptance of the product is.

28. Develop species for uniform seed, fruit, and tuber size and placement. Harvesting is simplified by consistent plant characteristics. Simplified harvesting equipment saves mass, volume, and power.

29. Determine a growth environment that supports increased oxygen production, CO2 removal, water transpiration, or food production. CELSS capability to act as an

ECLSS system depends on ability to adjust for changing needs. System designs must accommodate changes in primary CELSS mission.

30. Develop plant disease control and prevention techniques applicable to CELSS conditions.

31. Determine plant response to rapid heating and cooling based on Space Station orbital cycle.

32. Determine effect of CO_2 levels in root aeration atmosphere.

7.2 ENGINEERING RESEARCH AREAS

1. Develop PGU design using corrosion-resistant and nonphytotoxic material while maintaining a lightweight structure. The nutrient solution contains corrosive salts that will destroy structures made from conventional metals. The use of highly corrosion-resistant materials and plastics can reduce this problem. Accessibility, maintainability, and resupply are directly affected by this problem. Using lightweight plastics may reduce mass. Off-gassing plastics may require additional ECLSS equipment and/or processes.

2. Develop thermal control system with minimum energy and volume penalty to remove lighting heat load. Lighting imparts multiple kilowatts of heat energy into the CELSS module. Developing optimized air and fluid cooling combinations are needed to reduce thermal control system power and volume requirements.

3. Develop electrical power generation system using waste heat generated by lighting system. Adapting thermal collectors may generate large temperature differentials usable for electrical power generation. Power generation using thermister principles are found in popular literature using a temperature difference of 250^{o}F. Electric power limitations strongly impact CELSS design. Any power-producing system using waste heat can reduce power penalty. Increased mass, volume, and complexity penalty may be outweighed by the availability of increased power.

4. Develop nutrient fluid handling system that ensures adequate supply, constant monitoring, reconditioning and leakproof design in a microgravity environment. Continuous nutrient supply must be maintained to prevent crop failure. Nutrient solution requires constant reconditioning for pH and essential minerals. The nutrient solution's corrosive nature requires a high degree of containment to protect other CELSS systems. All parameters are affected by nutrient system design. Maintainability and automation are especially impacted.

5. Design a multiple-species plant harvesting unit. Balanced diet will require growth and harvest of multiple plant species. Volume and automation are affected by the number and variety of harvesting devices required to handle the different species. Initial study evaluation suggests a multiple species device is more volume effective and less difficult to automate than a series of single-crop harvesters.

6. Design a plant processing unit that can process numerous varieties of edible foods. Balanced diet will require consumption of multiple plant species. Volume and automation are affected by the number and variety of food processing devices required to handle the different food types. Initial study evaluation suggests a multiple-food device is more volume effective and less difficult to automate than a series of single-purpose harvesters.

7. Design robotic gardener for plant tending, processing, and equipment maintenance. Automation requires an active device to perform gardening-related operations. A mobile, intelligent device can concentrate these activities into minimum volume while attaining maximum flexibility and capability. Robotic gardener may require multiple, specialized tools to support additional tasks such as harvesting, planting and tray sterilization.

8. Design multiple species plant growth unit. Balanced diet will require consumption of multiple plant species. Volume, mass, power, and automation are affected by the number and variety of plant growth devices required to grow different plant species. Study evaluation suggests a multiple-species device is more effective and less difficult to maintain.

9. Design nutrient solution reconditioning system. Nutrient solution reconditioning enhances plant growth and reduces the frequency of new nutrient makeup. Reconditioning requires adjustment of pH minerals, trace elements, and the removal of particulates and phytotoxic chemicals. Reconditioning the nutrient solution reduces resupply requirements and power consumption by the waste regeneration system used to dispose of used nutrient solution.

10. Design fiber optic cables for unbroken runs from solar collectors to terminal illuminators. Every connector in fiber optic cables can reduce light levels 2 to 3 dB. This significant loss can be prevented by using a continuous fiberoptic cable from collector to plants. Continuous cable design reduces the number of collectors and thus require fewer collectors. This reduces the mass launched to orbit and on-orbit power requirements. Secondary maintenance and reliability advantages occur because connectors are not required.

11. Design microgravity adapted supercritical water oxidation (SCWO) system. Current SCWO size and equipment are for use in hazardous waste processing on Earth. Redesign for space application should reduce volume, mass, and power requirements. Redesign allows safety, maintenance, and reliability features specifically for Space Station applications.

12. Design tray sterilization system using nontoxic process. Tray sterilization reduces incidence of plant pathogen spread to new plants. Nontoxic techniques reduce chances that a hazardous material will be released into CELSS atmosphere. Tapping into thermal system to use waste heat for steam generation provides one approach.

13. Design columnar luminares (light fixtures) for use with HID lamps. HID lamps are the most efficient artificial light source available. Even distribution of HID-generated light to plants requires precisely designed luminares.

7.3 ADVANCED TECHNOLOGY RESEARCH AREAS

1. Develop fiber optic solar collector system to transmit solar illumination to plant growth area. Solar light directly transmitted to plants can significantly reduce power requirements. Direct illumination, using windows, possess many technical

design problems that affect crew safety. Remote solar light collection and transmission using fiber optic cables provides an alternative approach. Fiber optics also permit precise light distribution and intensity control. Prototype systems exist with 60% transmission efficiency. Artificial lighting efficiency is 4% to 5% from solar collector to plant light.

2. Develop fiber optic cable specifically tuned to visible light. Currently available fiber optics are tuned to higher communication frequencies. Transmission improvements are possible with a frequency-tuned fiber optic cable. This cable design can include components absorbent to IR and UV frequencies. This feature will reduce critical lens alignment features of the "HIMIWARI" solar collector identified in this study.

3. Develop fiber optic cable connectors to reduce light-loss levels at cable switching and connecting points. Current connectors impose 2- to 3-dB loss at each connector. This loss requires more solar collectors to compensate for light loss. More collectors increase mass, power, and maintenance requirements.

4. Develop SCWO system for use in microgravity environment. SCWO prototypes demonstrate very high efficiencies (99.995%) in organic waste oxidation. This system could potentially handle all CELSS wastes while producing carbon dioxide, potable water, and nitrogen gas. The system also recovers nutrient salts and oxides. System adaptation will require development of (1) high pressure, low volume, fluid pumps capable of processing corrosive fluids with high particulate loads, (2) high-pressure fluid/gas and gas/gas separators; (3) waste pulverizer to reduce biomass to very fine particulates. 4) high-pressure heat exchangers.

5. Develop a steam turbine generator to operate from SCWO system. This system can operate exothermically using 5% or more organic waste effluent. Reaction pressure and temperature indicate that a turbine could operate from SCWO output. This turbine could supply electrical power or compressed air to the Space Station.

6. Develop inedible-to-edible biomass conversion systems. Maximizing food value return from each plant grown requires processing the inedible material into an edible format. Power, mass, and volume requirements could be reduced with more

efficient biomass conversion. Biological and physiochemical biomass recovery systems should be investigated.

7. Develop artificial intelligence programs required by robotic gardener. Labor-hours are saved using a robot to perform routine CELSS chores. Additional savings occur with increased robotic artificial intelligence capability. Robot tasks include plant health monitoring, seeding, harvesting, and plant tray manipulation.

8. Develop high-efficiency, mercury-free lights for use in microgravity. Modern high-efficiency lights (high pressure sodium, high-intensity discharge) use mercury as an amalgam component. Highly toxic mercury is prohibited in the Space Station closed environment. Amalgam pooling or positioning is critical to lamp operation. Microgravity conditions may prevent pooling or positioning.

9. Develop aeroponic plant growth systems that are operable in microgravity CELSS conditions. Mass, volume, and power penalties are lowest in aeroponics systems. Root oxygenation, nutrient transfer and temperature control are not well defined. Tubers fail to develop normally in aeroponic systems.

10. Develop plant seeding tape for use on accordion growth trays. Automated seeding requires positive seed control and placement in microgravity. Seed tape must adhere to damp surfaces, retain plants in position, promote plant growth, aid in germination, retain structural integrity for growth cycle, and prevent fluid escape from plant growth tray. This tape is a necessary component of this studies selected plant growth concept.

11. Develop pH and ion probes for monitoring nutrient solution. These probes must work in microgravity with low maintenance reliability, and accuracy at low concentrations. Probes must be ion specific.

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8.0 CELSS REQUIREMENTS

Growing higher vascular plants under microgravity conditions in a Space Station module provides the background for CELSS requirements definition. The requirements were identified and evaluated in 19 design areas.

8.1 Plant illumination.
8.2 Plant nutrient supply.
8.3 Water management.
8.4 Thermal control.
8.5 Automation.
8.6 Plant growth structure.
8.7 Atmosphere control system.
8.8 Tropism.
8.9 Phytotoxicity control.
8.10 Plant gas exchange.
8.11 Plant spacing.
8.12 Utility routing.
8.13 Accessibility and maintenance.
8.14 Data collection and management.
8.15 Plant harvesting systems.
8.16 Food processing systems.
8.17 Waste regeneration.
8.18 Pathogen control.
8.19 Robotic systems.

CELSS operation scenarios establish the constraints within which requirements are evaluated to define the best CELSS systems designs. For example, when electrical power supply becomes more containing than growth cycle interval, lighting intensities are reduced to accommodate available power while accepting longer growth cycles. Certain parameters (power, mass, volume, and cost) are strongly impacted by design requirements. For example, electrical power varies with lighting and thermal requirements while volume responds mostly to PGU design. Therefore, while specific values are stated in requirements, they should be considered engineering estimates that are interdependent on other system designs.

8.1 PLANT ILLUMINATION REQUIREMENTS

1. Provide 10 to 1000 micromol/m^2/s illumination. This requirement covers lighting needs of plants considered for CELSS.

2. Heat generation in the vicinity of plants shall be evenly distributed across the plant canopy to avoid hot spots. Heat generated should not exceed the thermal dissipation system's rated capacity.

3. Equal light intensity shall be provided to all plants at the same growth stage.

4. Minimize light source electrical power, volume, and mass demands.

8.2 PLANT NUTRIENT SUPPLY REQUIREMENTS

1. Plant nutrients shall be supplied by recycling Space Station wastes.

2. Automatic monitoring and replenishment of nutrients shall be provided.

3. Nutrient delivery to plants shall be via aeroponics (mist spray on root masses), or hydroponics.

4. Excess nutrient shall be removed from root vicinity.

5. Dissolved oxygen content of nutrient shall be three to nine ppm.

8.3 WATER MANAGEMENT REQUIREMENTS

Any available water sources may be used by CELSS. Potential water sources are-

1. SCWO condensate recovery from Space Station waste water including hygiene, wash, and urine flush water, optionally including fecal wastes.
2. Recycled, depleted nutrient solution.

3. Condensate recovery of plant transpired water.

4. Space Station potable water.

8.4 THERMAL CONTROL REQUIREMENTS

1. Thermal control shall be provided to maintain CELSS module temperatures of 20°C to 30°C.

2. Thermal control shall be provided to maintain optimum plant canopy temperature range for plants.

8.5 AUTOMATION REQUIREMENTS

1. CELSS routine operations shall be autonomous.

2. Human attention to CELSS shall be minimized by automation and robotics.

3. Equipment repair and maintenance shall be performed by crew members.

4. Repairs shall be made at orbital replacement unit (ORU) level.

5. All function shall be provided by system-sensor monitoring, with fault identification provided by CELSS computer.

8.6 PLANT GROWTH STRUCTURE REQUIREMENTS

1. Plants shall be securely fixed to their growth tray or growth device.

2. A physical separation shall exist between plant root zone and aerial parts. This separation shall prevent exchange of gases and fluids between roots and plant atmospheric parts.

3. Roots shall be shielded from light.

4. Vertical air circulation from tray surface to plant canopy is required.

8.7 ATMOSPHERE CONTROL SYSTEM REQUIREMENTS

1. Plant canopy and root zone atmosphere compositions shall be maintained independently.

2. Conditioned air circulation shall be used to maintain plant canopy humidity control.

8.8 EXTERNAL PLANT STIMULI REQUIREMENTS

1. Roots shall not be exposed to light.

2. Vibration levels shall be below plant response threshold.

3. Airflow shall flow from plant base to canopy to influence plant orientation.

4. Potential electromagnetic field effects on plant orientation shall be considered when placing electrical utilities.

8.9 PHYTOTOXICITY CONTROL REQUIREMENTS

1. Nutrient makeup system and CELSS shall remove plant toxin accumulation. Some toxins to be considered are ethylene, ozone, heavy metals, and fluorides.

8.10 PLANT GAS EXCHANGE REQUIREMENTS

1. Airflow shall be used to maintain humidity, temperature, carbon dioxide, and oxygen levels.

2. Air exchange rate shall range from 0.42 to 1.1 m^3/s.

8.11 PLANT SPACING REQUIREMENTS

1. Plants shall be spaced to optimize volume usage and light distribution.

2. Transplantation shall not be used to provide optimum plant spacing.

8.12 UTILITY ROUTING REQUIREMENTS

1. Utilities shall be available to plant growth units to provide nutrient and air exchange functions.

8.13 ACCESSIBILITY AND MAINTENANCE

1. Human access to plants shall be provided.

2. Plant growth units shall be designed for modular service.

3. Plant growth units shall not be deactivated for partial system service.

4. CELSS shall conform to modular standards that apply to the Space Station.

8.14 DATA COLLECTION AND MANAGEMENT REQUIREMENTS

1. Sensors shall monitor all CELSS operations.

2. CELSS system operations are implemented by the CELSS computer to reflect changes in operating conditions.

3. CELSS computer shall generate failure alerts to Space Station computer for failures beyond the automated systems capability to modify or adjust.

8.15 PLANT HARVEST SYSTEMS REQUIREMENTS

1. Harvesting shall be autonomous for normal operation.

2. Plant harvesting shall utilize robots.

3. Harvest equipment shall operate only on light-side orbit.

4. Harvest devices shall have the capability to process wheat, soybeans, and potatoes.

8.16 FOOD PROCESSING SYSTEMS REQUIREMENTS

1. Food processing shall be autonomous in normal operation.

2. Minimum food processing preparation shall be required for crop storage.

8.17 WASTE REGENERATION REQUIREMENTS

1. Waste management system shall be based on the SCWO.

2. Waste management system shall provide water, carbon dioxide, and salts for the CELSS.

3. Space Station wastes, except fecal wastes, shall be processed by the SCWO system.

8.18 PATHOGEN CONTROL REQUIREMENTS

1. CELSS module shall provide sterilization of plant enclosures, harvest equipment, and food processing equipment to prevent bacteria propagation.

2. Sterilization processes shall not pose any immediate or residual threat (e.g., chemical processes that leave a phytotoxic residue on trays).

8.19 ROBOTIC SYSTEMS REQUIREMENTS

1. CELSS robot performs routine plant growth and harvesting tasks.

2. CELSS robot shall interface with automated plant growth units, seeder, and harvest equipment.

3. CELSS robot shall be limited in CELSS system repair and maintenance capability.

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MICROMOLE PER SECOND PER SQUARE METER MEASUREMENTS

(Micromole/S/M^2)

To obtain micromole S^{-1} M^{-2} measurements multiply footcandle readings by the given constants depending on the lamp type.

LAMP TYPE	Multiply FC by the given constant for micromole S^1 M^{-2} conversions**	
	400-700 nm	400-850 nm
Daylight (Sun and Sky)*	0.20	0.30
Blue sky only*	0.21	0.26
High Pressure Sodium	0.13	0.20
Metal Halide	0.15	0.18
Mercury Deluxe	0.13	0.14
Warm White Fluorescent	0.14	0.15
Cool White Fluorescent	0.15	0.15
Standard Gro-Lux Fluorescent	0.33	0.35
Wide Spectrom Gro-Lux Fluorescent	0.20	0.23
Incandescant	0.22	0.54
Low Pressure Sodium	0.10	0.12

*Typical of clear summer sky at 40° latitude

**These are generic values based on Thimijan and Heins (Horticulture Science, 18:818, 1983), and McCree (Agricultural Meteorol, 10:443, 1972)

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SPECTRAL POWER IN ARBITRARY COLOR BANDS (WATTS & PERCENT OF TOTAL EMMISSION) METALARC LAMPS

COLOR BANDS (NM)			M1000		M1000/C		MS1000		MS1000/C		MS1000/3K	
			Watts	%	Watts	%	Watts	%	Watts	%	Watts	%
Ultra Violet		380	33.7	8.8	25.2	6.3	30.5	7.0	15.6	3.8	6.0	1.7
Violet	380	-430	57.3	15.0	63.9	15.9	59.9	13.7	61.3	15.0	29.3	8.2
Blue	430	-490	44.6	11.7	52.6	13.1	50.7	11.6	50.0	12.3	31.0	8.6
Green	490	-560	70.4	18.4	83.2	20.7	82.2	18.8	83.8	20.5	73.3	20.5
Yellow	560	-590	51.1	13.3	61.2	15.3	63.1	14.5	56.3	13.8	13.8	17.1
Orange	590	-630	76.6	20.0	70.3	17.5	90.8	20.8	85.3	20.9	99.4	27.7
Red	630	-700	32.9	8.6	28.5	7.1	39.9	9.1	35.6	8.7	44.0	12.3
Far-Red	700	-800	16.3	4.3	16.7	4.1	19.6	4.5	20.3	5.0	14.1	3.9
TOTAL			382.9	100.0	401.6	100.0	436.7	100.0	408.2	100.0	358.5	100.0

Christos C. Mpelkas
Photobiologist
April/1985

TABLE OF REFERENCE VALUES

Ref Topic	Value	Source
Light Level 0-20 days wheat	500mm/m2/sec	Bugbee 4/9/85
Max usable light level	1000mm/m2/sec	Bugbee 4/9/85
Natural Daylight light level	10000 ftcndl	F. Buck @ GE
Leaf crop light requirement	1000+ ftcndl	F. Buck @ GE
Fluorescent-canopy spacing	6 inches min	F. Buck @ GE
HID canopy spacing	12 inches min	F. Buck @ GE
S. Station ambient CO_2	2000ppm	R. Ames ECLSS
Module outside diameter	14ft	SS ref Config
Module inside diameter	13ft 8in	SS ref Config
HID heat load w/ballast		
1000 watts	3750 btu/hr	Sylvania Co.
400 watts	1600 btu/hr	Sylvania Co.
100 watts	400 btu/hr	Sylvania Co.
Micromoles/m_2/sec to		
foot-candle ratio (approx)	1:10	R. MacElroy 3/15/85
Ballast load as % bulb rating	10-20%	GE Seattle Staff
HP Sodium light emitter size	80mm x 9.5mm	GE Seattle Staff
Solar Light Constant	1353 watts/m_2	Dr. K. Mori
Solar Ray collector efficiency	60%	Dr. K. Mori
Solar Ray collector pointing	.02 degree	Dr. K. Mori
Minimum optical cable temp	-20° degree	Dr. K. Mori
Lumens from 3.17m^2 solar ray		
Collector @ 50% efficiency		
in orbit.	500,000 lumens	Dr. K. Mori

TABLE OF REFERENCE VALUES (Continued

Ref Topic	Value	Source
Grams oxygen/liter std atmo	1.429	CRC handbook
Average % biomass containing hydrogen, carbon & nitrogen	89%	Fundamental Chem
Average % carbon & hydrogen in carbon, hydrogen nitrogen	75%	Fundamental Chem
Potatoes transpiration @ 400mm 20° 325ppm CO_2	5.4 L/m2/d	Tibbits 12/21/84
Potatoes light requirement	400-700 mm m2/sec	Tibbits 12/21/84
Potato light cycle	24 hr light	Tibbits 12/21/84
Potato growth temp	20° Cent	Tibbits 12/21/84
Potato growth humidity	70%	Tibbits 12/21/84
Potato plant dimensions	24" high x 20" diameter	Tibbits 12/21/84
Potato plant spacing	.2m2/plant	Tibbits 12/21/84
Potato maturity early	56 days	Tibbits 12/21/84
nominal	105-140 days	Tibbits 12/21/84
Potato canopy temperature Variance from air temp.	2° Cent	Tibbits 12/21/84
Potato toxins	Selenium	Tibbits 12/21/84
Potato biomass (total)	38 g/m2/d	Tibbits 12/21/84
(edible)	20.7 g/m2/d	Tibbits 12/21/84
Potato harvest index	.53	Tibbits 12/21/84

TABLE OF REFERENCE VALUES (Continued

Ref Topic	Value	Source
Soybeans		Dr. D. Raper
Illumination level (max)	700 mm/m2/sec	Dr. D. Raper
(min)	350 mm/m2/sec	Dr. D. Raper
Light cycle (light)	9-12 hr/24/hr	Dr. D. Raper
(dark)	12-15 hr/24hr	Dr. D. Raper
Air temperature (range)	22-28^o Cent	Dr. D. Raper
Air temperature (nominal)	26^o Cent	Dr. D. Raper
Root temperature (nominal)	24^o Cent	Dr. D. Raper
CO_2 levels	400-600 ppm	Dr. D. Raper
Canopy temperature variance		
from air temp	4^o Cent	Dr. D. Raper
Tray depth	30-35 cm	Dr. D. Raper
Maturity (early)	90-120 days	Dr. D. Raper
(nominal)	100 days	Dr. D. Raper
Germination time (dark)	48 hrs	Dr. D. Raper
Plant height (30^o C.)	1.8 meters	Dr. D. Raper
(18^{o}C.)	0.5 meters	Dr. D. Raper

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1. Report No. NASA CR- 177421	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Controlled Ecological Life Support Systems (CELSS) Conceptual Design Option Study		5. Report Date June 1986
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12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 24056		14. Sponsoring Agency Code 199-61-12

15. Supplementary Notes

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16. Abstract

This document contains the results of a study designed to explore options for the development of a Controlled Ecological Life Support System (CELSS) for a future Space Station. In addition, study results will benefit the design of other facilities such as the Life Sciences Research Facility, a Ground-Based CELSS demonstrator and will be useful in planning longer range missions such as a lunar base or manned Mars mission. The primary study objectives were to develop weight and cost estimates for one CELSS module selected from a set of preliminary plant growth unit (PGU) design options. Eleven Space Station CELSS module conceptual PGU designs were reviewed, components and subsystems identified and a sensitivity analysis of CELSS subsystems performed. Areas were insufficient data is available were identified and divided into the categories of biological research, engineering research and technology development. Topics which received significant attention in this report were lighting systems for the PGU, the use of automation within the CELSS system and the electrical power requirements of the system. Other areas examined included plant harvesting and processing, crop mix analysis, air circulation and atmosphere contaminant flow subsystems, thermal control considerations, utility routing including accessibility and maintenance and nutrient subsystem design. Extensive analysis of the waste processing subsystem was done and included as an Appendix to this study. That Appendix is published as a separate NASA Contractor Report.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
CELSS, Plant growth systems, lighting systems, Space Station modules, automation, sensitivity analysis	Unclassified - Unlimited STAR Category 54

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